OFFICE OF INDUSTRIAL TECHNOLOGIES

MOTOR CHALLENGE

United States Industrial Motor Systems Market Opportunities Assessment

OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY
U.S. DEPARTMENT OF ENERGY

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MOTOR CHALLENGE

PREPARED FOR
THE U.S. DEPARTMENT OF ENERGY'S
OFFICE OF INDUSTRIAL TECHNOLOGIES AND
OAK RIDGE NATIONAL LABORATORY
(OPERATED BY LOCKHEED MARTIN ENERGY RESEARCH, INC.)

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Executive Summary

PROJECT OBJECTIVES

This is the *Final Report of the United States Industrial Electric Motor System Market Opportunities Assessment.* The Market Assessment is one component of the United States Department of Energy's (DOE's) Motor Challenge Program. Motor Challenge is an industry/government partnership designed to help industry capture significant energy and cost savings by increasing the efficiency of motor systems. DOE's primary strategy is to support plant managers in applying a systems approach to specifying, purchasing, and managing electric motors and related machines so as to minimize the electricity needed to achieve production goals. This Market Assessment is intended to serve as a blue print for the implementation of the Motor Challenge strategy.

The objectives of the Market Assessment are to:

- Develop a detailed profile of the current stock of motor-driven equipment in U.S. industrial facilities;
- Characterize and estimate the magnitude of opportunities to improve the energy efficiency of industrial motor systems;
- Develop a profile of current motor system purchase and maintenance practices;
- Develop and implement a procedure to update the detailed motor profile on a regular basis using readily available market information; and,
- Develop methods to estimate the energy savings and market effects attributable to the Motor Challenge Program.

In addition to serving DOE's program planning and evaluation needs, the Market Assessment is designed to be of value to manufacturers, distributors, engineers, and others in the supply channels for motor systems. It provides a detailed and highly differentiated portrait of their end-use markets. For factory managers, this study presents information they can use to identify motor system energy savings opportunities in their own facilities, and to benchmark their current motor system purchase and management procedures against concepts of best practice.

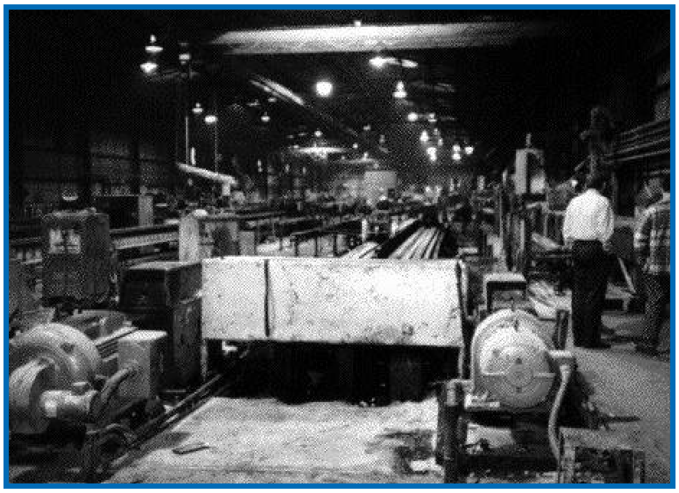
The Market Assessment was carried out by XENERGY Inc. under a subcontract with Oak Ridge National Laboratory (Lockheed Martin Energy Systems). The project was initiated in the autumn of 1995. Field data collection was carried out during most of calendar 1997. Many individuals and organizations contributed to this study. We would particularly like to thank the facilities managers and staff who permitted us to conduct inventories of their motor systems and the representatives of industry, government, and academic organizations who volunteered their time to review the study and its reports at various stages of development.

OVERVIEW OF FINDINGS

Magnitude of industrial motor system energy use and potential energy savings.

In 1994, electric motor-driven systems used in industrial processes consumed 679 billion kWh—23 percent of all electricity sold in the United States. These machines make up by far the largest single category of electricity end use in the American economy. Based on detailed analysis of the motor systems inventory, we estimate that industrial motor energy use could be reduced by 11 to 18 percent if facilities managers undertook *all cost-effective applications of mature proven* *efficiency technologies and practices.* That is, implementation of all well-established motor system energy efficiency measures and practices that meet reasonable investment criteria will yield annual energy savings of 75 to 122 billion kWh, with a value of \$3.6–\$5.8 billion at current industrial energy prices.[1] Many kinds of motor system efficiency improvements yield benefits in addition to energy cost reductions. These include improved control over production processes, reduction in waste materials, and improved environmental compliance.

Of course, this full potential cannot be captured all at once. That would require expenditures of \$11–\$17 billion, roughly 10 percent of total new capital expenditures by all manufacturers in 1994. While the opportunities for energy savings and other benefits associated with investments in improved motor systems are enormous, so too are the demands on capital and management resources in industrial organizations. Moreover, we identified many barriers which have prevented industrial facilities managers from capturing more than a small percentage of the potential benefits of motor system efficiency. These are described on page 4.



On average, the manufacturing sector could reduce industrial motor energy use by 11% to 18% using mature, proven efficiency technologies and practices. This Greenville Tube production facility reduced its annual energy use by 34% and saved \$77,266 annually through improving the efficiency of its tube drawing bench.

Categories and relative size of motor system energy savings opportunities.
There are two basic categories of motor system energy efficiency measures:

- Motor efficiency upgrades which improve the energy efficiency of the motor driving a particular machine or group of machines; and,
- System efficiency measures which improve the efficiency of a machine or group of machines as a whole. System efficiency can be improved by reducing the overall load on the motor through improved process or system design, improving the match between component size and load requirements, use of speed control instead of throttling or bypass mechanisms, and better maintenance, to name just a few of the engineering strategies available.

We estimate that motor efficiency upgrades can achieve potential savings of about 19.8 billion kWh per year. Improved methods of rewinding failed motors can contribute an additional 4.8 billion kWh. Energy savings from system efficiency improvements are potentially much larger: 37 to 79 billion kWh per year. Most motor efficiency upgrades can be achieved fairly easily by selecting the most efficient available motor for the application at hand. System efficiency measures, on the other hand, often require a significant amount of effort on the part of industrial end-users and their vendors to identify, design, implement, and maintain.

Progress to date: motor efficiency upgrades.
The Market Assessment Inventory (MAI) found that motors which meet federal efficiency standards which took effect in October 1997 account for 9.1 percent of the motors currently in use in manufacturing facilities. Such motors have been available for two decades. Between 1993 and 1996, they constituted about 18 percent of all motors sold in the 1–200 horsepower range

[1] We applied a guideline of a 3-year simple payback when questioning engineers and market experts regarding the applicability of common motor system efficiency measures. Average industrial energy price: \$0.048 per kWh. (EIA 1997)

covered by the efficiency standard.[2] In aggregate, efficient motors currently in place are saving industrial facilities 3.3 billion kWh per year, compared to motors of average efficiency sold previous to the promulgation of federal efficiency standards.

Replacement of general purpose AC induction motors currently in use with motors that meet federal efficiency standards will yield energy savings of 13.0 billion kWh per year. Replacement with the most efficient motors currently available will yield an additional 6.8 billion kWh in annual savings. Given patterns of new motor purchase and rewinding of failed motors documented here, it will take 15 to 20 years for current population 1–200 horsepower motors to be 80 percent replaced. The challenge for government and utility efficiency programs is to assist in accelerating the pace of replacement.

Progress to date: system efficiency measures.

The remaining 37 to 79 billion kWh in annual savings will be realized one project or plant at a time through the efforts of facilities managers, engineering and maintenance staff, designers, distributors, and manufacturers. A small number of companies, primarily multinational corporations in industries with high concentrations of motor system energy use, have enacted aggressive programs to identify and capture system improvement opportunities and to monitor and maintain these systems on an ongoing basis. These companies have been amply rewarded for their efforts. The Motor Challenge Program has documented over a dozen major projects that have yielded average system-level energy savings of 33 percent, and some as high as 60 percent. Within the manufacturing sector as a whole, installations of adjustable speed drives now in place yield 3–6 billion kWh in annual savings compared to conventional control mechanisms such as throttle valves and bypass loops. Common improvements to air compressor systems have yielded an estimated 1 billion kWh per year in additional savings.

Using system efficiency measures that included adjustable speed drives and energy-efficient motors on the supply air fan, 3M cut electricity use by 41% in one building and saved over $77,000 per year.

Despite the success of a few companies and the relative maturity of the technologies used to achieve motor systems efficiency, the level of knowledge and adoption of system efficiency measures among facilities managers is very low. Motor systems equipped with adjustable speed drives account for only 4 percent of manufacturing motor system energy, compared to a potential level of application between 18 and 25 percent. We found that only the largest plants had implemented the most common kinds of system improvements in the past 2 years to any great extent, and the pattern of knowledge and implementation, even among the largest companies, was inconsistent. Among all manufacturing facilities, 24 percent reported that they had not taken any of a long list of potential system efficiency measures over the past 2 years.

2 Standards contained in the Energy Policy Act (EPAct) of 1992 apply to all integral horsepower, general purpose, AC induction motors from 1–200 HP. Such motors constitute 50 to 70 percent of all motors sold in the relevant horsepower classes.

Barriers and solutions.

We and other researchers have found that industrial facilities managers face significant barriers to capturing the financial and operating benefits of motor system energy improvements. Among the most important are the following:

- Low priority of energy efficiency among capital investment and operating objectives. Within manufacturing as a whole, motor system energy costs constitute less than 1 percent of total operating costs. This figure is considerably higher for a small number of energy-intensive industries such as paper and chemicals.
- General lack of awareness among facilities managers, equipment distributors, engineers, and manufacturers' representatives of strategies to achieve motor system efficiency: their costs, management requirements, and benefits.
- Generally low level of staffing for the facilities maintenance function.
- Conflicting incentives for suppliers regarding the promotion of efficient equipment and practices. For example, compressed air distributors have greater incentive to sell additional compressors to customers with increasing load rather than to advise those customers how to control load growth through better maintenance and production planning.

Partnership solutions.

In order to capture the economic and environmental benefits of improved motor system efficiency, all participants in the motor systems markets—end-users, manufacturers, distributors, and designers—must develop new ways of doing business. Realizing the benefits of motor systems upgrades may be a relatively simple matter of adopting specifications for motor purchases and rewinds. To capture system efficiencies, facilities managers and their vendors, and consulting engineers will need to assess operations on a periodic basis to identify the major savings opportunities available in virtually every factory, then work together to design and implement the projects.

Facilities managers, their vendors, and consulting engineers will need to work together to identify and capture major savings opportunities.

No one group of market actors can accomplish this transformation working alone; the barriers of conflicting interests and resource constraints are simply too high. Rather, end-users and suppliers must identify where their business interests in motor systems efficiency coincide and develop ways to work together to realize those interests. The Motor Challenge Program is designed to assist market actors in accomplishing these objectives. Among the program's many achievements to date is the development of the MotorMaster+ motor selection software, which couples an electronic equipment catalog to a sophisticated economic analysis program to help customers select the most cost-effective motor for their needs. Not only has this software program been of direct benefit to end-users, but it has been distributed by motor vendors as a promotional tool for their energy-efficient lines. The Motor Challenge Program, guided by the results of the this Market Assessment and the advice of industry experts, continues to develop new initiatives to transform the market for industrial electric motor systems.

RESEARCH ACTIVITIES

THE MARKET ASSESSMENT INVENTORY

The principal research activity of this project was the Market Assessment Inventory (MAI). During calendar 1997, the assessment team conducted on-site studies of 265 industrial facilities on behalf of the DOE; 254 of these constituted a carefully designed probability-based sample of the entire manufacturing sector. An additional 11 non-manufacturing facilities were inventoried to provide case studies of motor system energy use in such industries as mining, agriculture, and water supply. The inventory was carried out in 20 metropolitan areas nationwide with additional sites in non-metropolitan areas. Figure E-1 shows the locations in which site studies were completed.

Figure E-1: Locations of MAI Activity

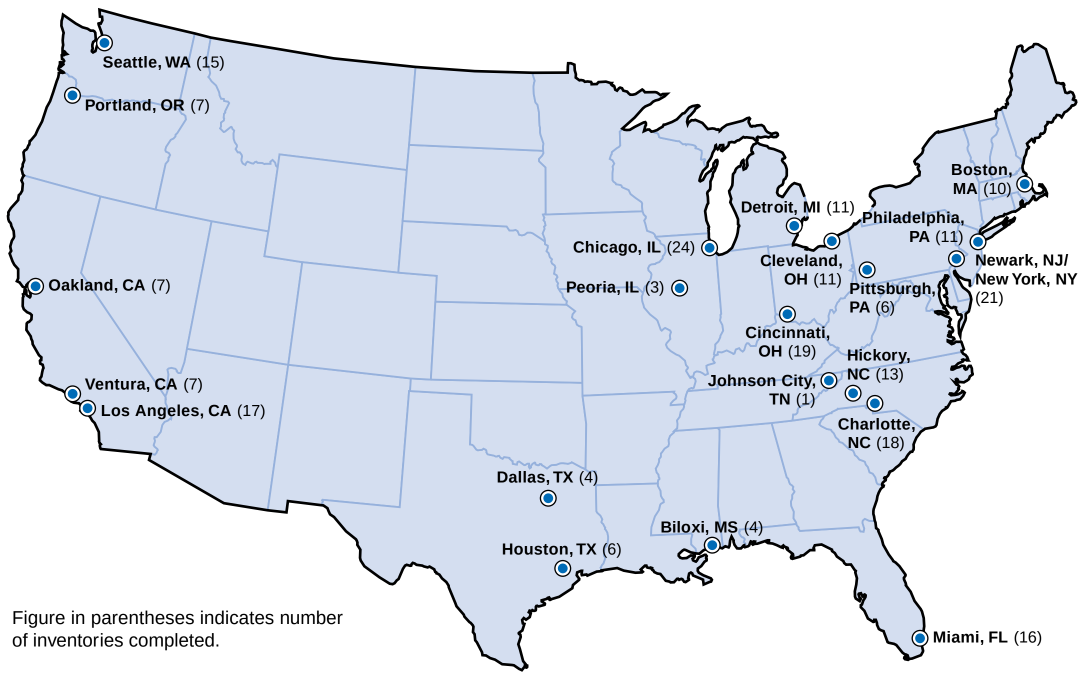


Figure in parentheses indicates number of inventories completed.

The MAI consisted of two parts: the Motor Systems Inventory and the Practices Inventory.

The Motor Systems Inventory.

For the Motor Systems Inventory, trained field engineers, accompanied by a representative of the plant, collected detailed information about every motor-driven system they could observe that was used in a production process. In very large plants, motor systems were sampled to contain the amount of time spent on site with the respondents' personnel. At each plant, the field engineer also worked with plant personnel to take instantaneous load measurements on a sample of motors. These measurements were used to estimate average part loads—a key element in estimates of energy use and potential savings. Through this process, we compiled detailed information on 29,295 motor systems—both the motor itself and the piece of equipment it drove. In addition, we compiled instantaneous load measurements on nearly 2,000 motor systems.

The Practices Inventory.

Achievement of significant increases in motor system efficiency depend to a large extent on the adoption of good design, purchase, and management practices. Equipment on the typical factory floor is constantly updated, reconfigured, and readjusted. Under normal patterns of use, motors wear out and need to be rebuilt or replaced every 7 to 10 years. Motor systems require continual monitoring and maintenance to run at their design efficiencies. Each decision and action in the daily stream of motor system design, purchase, and maintenance carries with it consequences for energy efficiency and consumption. The Practices Inventory gathered information on the prevalence of actions identified by industry experts as "good practice" in the sample facilities. The Practices Inventory also collected critical information needed to model the change in the motor systems population over time.

Accuracy of inventory results.
The results of any statistically based study such as the MAI are subject to error. Researchers generally identify two basic kinds of errors: sampling error and non-sampling error. In a properly structured study, sampling error can be quantified. We have done so for the most important quantities estimated—motor system energy for the population and key subgroups—using established statistical methods. Non-sampling errors arise due to difficulties in making accurate observations of the population of interest. The effects of these errors cannot be quantified on the basis of the observations themselves. However, they can be described qualitatively. Readers will best be able to understand and apply the results presented below if they understand the sources and sizes of these errors.

- Sampling error. Most of the description of the motor system population and energy savings opportunities contained in this report proceeds from estimates of motor system energy used by various groups of motor systems in the population. The assessment team estimated 90-percent confidence intervals for their estimates of total motor system energy in all manufacturing, total motor system energy in each two-digit manufacturing SIC group, and each major application (pumps, fans, air compressors, and other process systems).[3] The 90-percent confidence interval for total manufacturing motor system energy was ± 18 percent. The confidence intervals for total motor system energy in the individual two-digit SIC groups ranged from ± 4 percent (SIC 32: Stone, Clay, and Glass) to ± 81 percent (SIC 33: Primary Metals). The relatively large confidence intervals for Primary Metals and Chemical Products (± 46 percent) reflect the underlying diversity of the facilities found in those industries.
- Non-sampling error. The MAI posed many challenges to accurate observation of conditions in sample facilities. These are discussed throughout the report in the context of the specific observations they affected. The assessment team developed and implemented numerous data quality control procedures including: a complete manual review of completed inventories by a trained engineer; automated data quality checks on the raw data once entered; and a final round of "reality checking" on the partially processed data. Anomalous observations were referred back to the data collector or to our contacts at the participating sites for clarification and correction. Despite these precautions, we frequently needed to call on the judgment of site personnel or our field engineers to provide information which could not be directly observed or independently verified. These instances are noted throughout the report.

OTHER RESEARCH

This study supplemented the primary research of the MAI with extensive review of secondary sources and reanalysis of primary data sets including results of industrial facilities audits undertaken by utilities, motor system engineering studies carried out for various utility DSM programs, and the DOE Industrial Assessment Center Program database containing results of over 10,000 energy audits of small manufacturing facilities. The results of this research are reported in the *Interim Report* (XENERGY 1997) of this project. We draw upon these materials throughout this report to place the inventory findings in context.

[3] The 90-percent confidence interval is the range around the sample estimate that has a 90-percent probability of containing the actual population value of the parameter in question—in this case, total motor system energy.

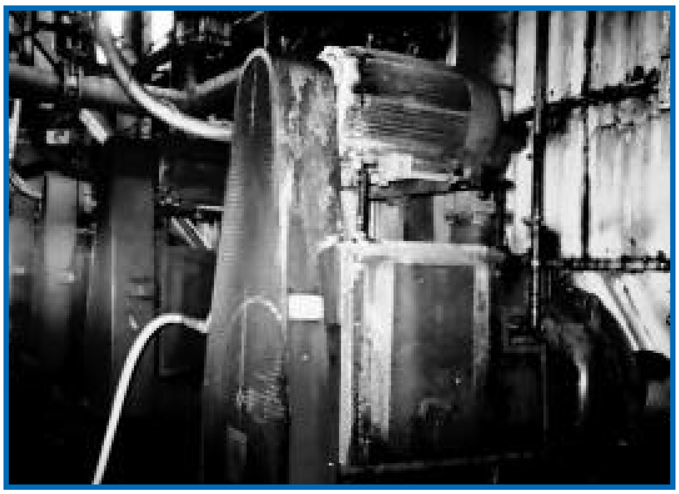
SUMMARY OF KEY FINDINGS

FINDINGS

Improvements in industrial motor system efficiency offer huge opportunities to invest in the enhanced efficiency and profitability of American industry. The key findings from this study concerning the nature and scope of those opportunities are as follows:

- Industrial motor systems represent the largest single electrical end use in the American economy. In 1994, industrial electric motor systems used in production consumed over 679 billion kWh, or roughly 23 percent of all electricity sold in the United States. Motors used in industrial space heating, cooling, and ventilation systems used an additional 68 billion kWh, bringing total industrial motor system energy consumption to 747 billion kWh, or 25 percent of all electricity sales. This is roughly equal to *total electric sales to the commercial sector in 1994 (795 billion kWh).*

- Potential industrial motor system energy savings using mature, proven, cost-effective technologies range from 11 percent to 18 percent of current annual usage or 62 to 104 billion kWh per year, in the manufacturing sector alone. Potential savings in the non-manufacturing industries are estimated at an additional 14 billion kWh. This is roughly equivalent to potential energy savings in such major commercial end-uses as indoor lighting. (XENERGY 1993) By way of comparison, all utility-sponsored demand-side management programs produced annual energy savings of 62 billion kWh in 1996. (EIA,b) The potential motor system energy savings for all industries translate into reductions in energy costs up to $5.8 billion, which directly increases the bottom line of industrial facilities. Realization of these savings would reduce carbon equivalent emissions by up to 29.5 million metric tons per year.



Improving the performance of this coal slurry pumping system has saved Peabody Holding Company 87,184 kWh per year. In U.S. industry, improvements to fluid systems represent over 60% of the overall industrial motor system energy savings potential.

- Improvements to the major fluid systems—pumps, fans, and air compressors—represent up to 62 percent of potential savings. This estimate does not include savings associated with improving the efficiency of the motors driving these systems. The technical aspects of optimizing pump, fan, and air compressor systems are well understood (if not widely implemented).

- For specific facilities and systems, potential savings far exceed the industry average. Motor Challenge has documented major cost-effective projects that have reduced energy consumption at the motor system level by an average of 33 percent, and by as much as 59 percent.

- Motor system energy use and energy savings are highly concentrated by industry and size of plant. Roughly 3,500 manufacturing facilities (1.5 percent of the total) account for nearly half of all motor system energy use and potential savings in the manufacturing sector.

- For industries that use significant amounts of motor system energy, the financial impact of motor system energy costs and potential savings are substantial. Most of the process industries with high levels of motor energy use operate on thin margins—on average 16 percent of operating revenues.[4] Any reductions in operating costs can substantially enhance profitability.

[4] Operating margin here corresponds to the quantity "Income from Operations" as defined in the *Quarterly Financial Report for Manufacturing, Mining, and Trade Corporations.* That is, Net Sales, Receipts, and Operating Revenues less Depreciation and all Operating Costs.

- The magnitude and patterns of motor system energy use and potential savings vary greatly among industries. Programs to assist industrial facilities in realizing motor energy savings must take these differences into account.
- Except in the largest facilities, the level of knowledge and implementation of systematic approaches to motor system energy efficiency is low. Although the engineering and industrial management community, with the support of Motor Challenge, has elaborated a set of best practices for motor systems design, purchase, and management, few companies are aware of these practices and fewer still have adopted them.
- Overcoming the barriers to adoption of efficient motor systems purchase and management practices will be difficult. These barriers include: conflicting priorities for capital investment, long capital replacement cycles, understaffing and under-training of plant maintenance and management functions, and conflicting motivations among equipment suppliers.

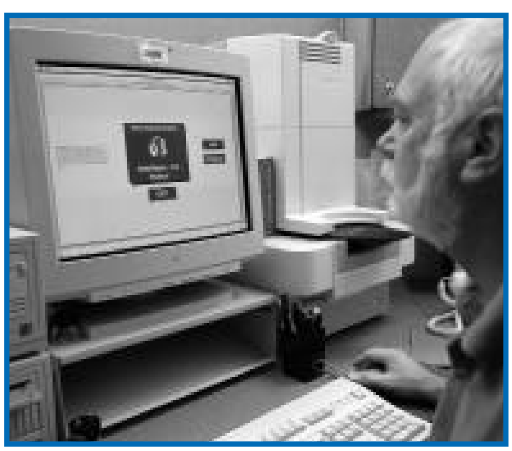
IMPLICATIONS FOR PROGRAM DESIGN

The findings of the Market Assessment provide a number of clear messages for the design of the Motor Challenge Program. These are as follows:

- Focus program resources on those industries and facilities in which the highest levels of energy savings are available. These are: Chemicals, Primary Metals (Steel & Aluminum), Paper and Allied Products, Water Supply and Wastewater, and Mining.
- Focus program resources on equipping manufacturers, designers, distributors, and purchasers of pump, fan, and compressor systems to specify and maintain optimized systems.
- Provide extensive and varied educational opportunities and tools for end-users to learn about and apply knowledge on efficient motors, motor system components, and motor system management.

Over the past 2 years, the Motor Challenge Program has implemented various components which take account of the market intelligence provided by this project. These initiatives include the following:

- Partnerships with end-user industry organizations. Motor Challenge is currently developing joint programs with the Technical Association of the Pulp and Paper Industry, the Association of Iron and Steel Engineers, the American Water Works Association, the Water Environment Federation, and the National Mining Association to reach plant engineers and managers in these industries.
- Partnerships with supplier organizations. Motor Challenge is pursuing a number of joint programs and initiatives with the industry associations that represent manufacturers and distributors of pump, fan, and compressed air systems. These programs include training for end-users, development of information products and design decision tools, and efficiency test protocols.



Tools like MotorMaster+ 3.0 can help industry capture energy savings opportunities and related cost and productivity benefits.

- Educational resources. Motor Challenge offers a broad range of educational products targeted to end-users. These include the MotorMaster+ computerized motor management tool, a technical information hotline, Showcase Demonstration case studies, and a host of other useful publications.

The Motor Challenge Program will continue to refine these offerings to help industry realize the motor energy savings opportunities and related economic benefits identified by the Market Assessment Study.

KEY FINDINGS: SELECTED DETAILS

Industrial motor systems represent the largest single electrical end use in the American economy.

- In 1994, motors systems used for production processes only (not including facility heating and ventilating) consumed 679 billion kWh, or 23 percent of all electricity sold in the United States that year (2,931 billion kWh). If the energy associated with industrial HVAC systems is added, this total comes to 747 billion kWh, or 25 percent of all electric sales.
- Process motor system energy accounts for 63 percent of all electricity used in industry.

Table E-1 shows the distribution of motor system energy use by major industry groups.

Table E-1: Motor System Energy Use by Major Industry Group

Industry Categories	Net Electric Demand* (million kWh)	Motor System Energy (million kWh)	Motor System Energy as % of Total Electricity
Manufacturing	**917,834**	**541,203**	**59%**
Process Industries (SICs 20,21,22,24,26,27,28,29,30,31,32)	590,956	419,587	71%
Metal Production (SIC 33)	152,740	46,093	30%
Non-metals Fabrication (SICs 23,25,36,38,39)	106,107	50,031	47%
Metals Fabrication (SICs 34,35,37)	68,031	25,492	37%
Non-Manufacturing	**167,563**	**137,902**	**82%**
Agricultural Production (SICs 01, 02)	32,970	13,452	41%
Mining (SICs 10, 12,14)	44,027	39,932	90%
Oil and Gas Extraction (SIC 13)	33,038	29,866	90%
Water Supply, Sewage, Irrigation (SICs 494, 4952,4971)	57,528	54,652	95%
Total All Industrial	***1,085,397***	***679,105***	***62.6%***

* 'Net Demand for Electricity' is the sum of purchases, transfers in, and total on-site electricity generation, minus sales and transfers off site. See MECS 1994 Table 12A-B.

Estimates of potential motor system energy savings in the manufacturing sector using mature, proven, cost-effective technologies range from 62 to 104 billion kWh per year, or 11 to 18 percent of current motor system energy use.

Savings estimation methods.
We estimated potential energy savings for motor efficiency upgrades and correction of motor oversizing by applying standard engineering formulae to observations of each motor system inventoried to which the measure would apply. Determining whether system efficiency measures apply to a particular motor system requires more data, time, and professional judgment than could be brought to bear in the course of the inventory. We therefore developed and implemented the following three-step process for estimating potential energy savings from the inventory data:

1. Estimate total energy usage by major application. We used the results of the inventory to estimate energy use by major application category: pumps, fans, air compressors, and other process systems.
2. Compile expert opinion and case studies on measure applicability and savings fractions. We solicited the opinions of industry experts—primarily consulting engineers, manufacturers' technical staff, and industry association representatives—regarding the percentage of systems to which various measures in the major application categories could be cost-effectively applied. We also solicited their opinions on the average savings these measures could achieve, in terms

of percentage of initial system energy use. We gathered similar information from case studies and other documents. Using this information, we formulated high, low, and midrange estimates of potential savings for each principal measure type within the major motor system application categories.

3. Calculate high, low, and midrange savings estimates. The savings estimates were calculated by applying the following formula:

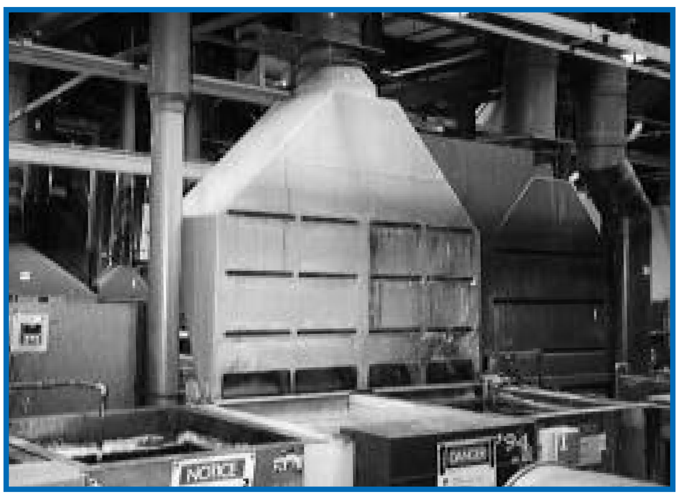
$$\textit{Applicability}_{\,(High, Midrange, Low)} \times \textit{Average Savings Fraction} \times \textit{System Energy.}$$

Because the motor systems grouped under "Other Process Systems" are so diverse, we did not feel it would be appropriate to apply to them the savings estimation process described above. Rather, we applied the method for speed control measures alone. Thus, the potential savings for this category is likely to be somewhat underestimated.

Throughout this analysis, we used a 3-year simple payback as the economic threshold for estimating applicability factors. These savings estimates can be understood as the economic potential for motor system efficiency improvements in existing industrial facilities.

Distribution of potential savings by type of measure.

Table E-2 shows how potential savings are distributed among different kinds of measures and end uses in manufacturing only. Potential efficiency improvements in non-manufacturing facilities add another 14 billion kWh in annual savings. The savings in the major groups of measures are additive. The term "CEE Efficiency Levels" refers to a set of motor efficiency standards proposed by the Consortium for Energy Efficiency, which are somewhat higher than the standards recently promulgated by the federal government. Nearly two-thirds of all potential savings derive from system improvements, such as the substitution of adjustable speed drives for throttling valves or bypass loops in pumping systems or fixing leaks in compressed air systems. Improvements to the major industrial fluid systems—pumps, fans, and air compressors—present between 45 and 62 percent of the total savings opportunities, taking into account low and high estimates.



General Dynamics Armament Systems' (formerly Lockheed Martin Armament Systems') ASD retrofit has resulted in annual savings of more than $68,000, with a 1.5 year payback.

Economic and environmental impacts of potential motor system energy savings in manufacturing.

Potential motor system energy savings carry significant impacts for the national economy and environment.

- Potential savings would reduce greenhouse gas emissions by 15.3 to 26.0 million metric tons of carbon per year.
- These savings are equivalent to removing 3.2 to 5.4 million cars from the road.

- The monetary value of these savings (after accounting for the price effects of self-generation) is $3.0 to $5.0 billion per year.
- In addition to energy savings, these improvements will yield a number of other economic benefits, including increased control over manufacturing processes and higher levels of quality control.

Table E-2: Summary of Motor Energy Savings Opportunities by Measure in Manufacturing Facilities

	Potential Energy Savings GWh/Year			Midrange Savings as Percent of	
Measure	Low**	Midrange**	High**	Total Motor System GWh	System-Specific GWh
Motor Efficiency Upgrades*					
Upgrade all integral AC motors to EPAct Levels***		13,043		2.3%	
Upgrade all integral AC motors to CEE Levels***		6,756		1.2%	
Improve Rewind Practices		4,778		0.8%	
Total Motor Efficiency Upgrades		24,577		4.3%	
Systems Level Efficiency Measures					
Correct motor oversizing	6,786	6,786	6,786	1.2%	
Pump Systems: System Efficiency Improvements	8,975	13,698	19,106	2.4%	9.6%
Pump Systems: Speed Controls	6,421	14,982	19,263	2.6%	10.5%
Pump Systems: Total	15,396	28,681	38,369	5.0%	20.1%
Fan Systems: System Efficiency Improvements	1,378	2,755	3,897	0.5%	3.5%
Fan Systems: Speed Controls	787	1,575	2,362	0.3%	2.0%
Fan Systems: Total	2,165	4,330	6,259	0.8%	5.5%
Compressed Air Systems: System Eff. Improvements	8,559	13,248	16,343	2.3%	14.6%
Compressed Air Systems: Speed Controls	1,366	2,276	3,642	0.4%	2.5%
Compressed Air Systems: Total	9,924	15,524	19,985	2.7%	17.1%
Specialized Systems: Total	2,630	5,259	7,889	0.9%	2.0%
Total System Improvements	36,901	60,579	79,288	10.5%	
Total Potential Savings	***61,478***	***85,157***	***103,865***	***14.8%***	

* Potential savings for Motor Efficiency Upgrades calculated directly by applying engineering formulas to Inventory data.
** High, Medium, and Low savings estimates for system efficiency improvements reflect the range of expert opinion on potential savings.
***Includes savings from upgrades of motors over 200 HP not covered by EPAct standards.

For specific facilities and systems, potential savings far exceed the industry average. Motor Challenge has documented major cost-effective projects that have reduced energy consumption by an average of 33 percent, and by as much as 59 percent at the system level.

Table E-3 summarizes the results of 13 motor systems efficiency projects supported and documented by Motor Challenge as part of its Showcase Demonstration component. Most of these projects involved assessment of and adjustments to fluid systems such as pumps, fans, and compressors, often accompanied by the addition of adjustable speed drives (ASDs) for speed control.

- These projects achieved energy savings of 38.6 million kWh per year at an average payback of 1.5 years.
- The high system-level savings are not atypical of these kinds of projects. There are many case studies of similar kinds of projects in the literature, and savings of this magnitude are reported by industry experts.

Table E-3: Summary of Motor Challenge Showcase Demonstration Projects

Company	Type of Plant	Energy Savings kWh/Year	Savings as % of Initial Sys. Energy	Annual Cost Savings	Payback on Investment (Years)
General Dynamics	Metal fabrication	451,778	38%	$68,000	1.5
3M Company	Laboratory facility	10,821,000	6%	$823,000	1.9
Peabody Coal	Coal processing	103,826	20%	$6,230	2.5
Stroh Brewery	Beer brewing	473,000	52%	$19,000	0.1
City of Milford	Municipal sewage	36,096	17%	$2,960	5.4
Louisiana-Pacific	Strand board	2,431,800	50%	$85,100	1.0
City of Trumbull	Sewage pumping	31,875	44%	$2,614	4.6
Nisshinbo California	Textiles	1,600,000	59%	$100,954	1.3
Greenville Tube	Stainless steel tubing	148,847	34%	$77,266	0.5
Alumax	Primary aluminum	3,350,000	12%	$103,736	0.0
OXY-USA	Oil field pumping	54,312	12%	$5,362	0.5
City of Long Beach	Waste incineration	3,661,200	34%	$329,508	0.8
Bethlehem Steel	Basic oxygen furnace steel mill	15,500,000	50%	$542,600	2.1
Total/Average		***38,663,734***	***33%***	***$2,166,330***	***1.5***

Motor Challenge Showcase Demonstration site, Nisshinbo California, Inc., improved their ventilation system energy efficiency by 59%, cutting costs by over $100,000 per year.

Motor system energy use and energy savings are highly concentrated by industry and size of plant.

- As Table E-4 shows, the top 10 motor system energy consuming four-digit SIC groups account for nearly half of all manufacturing motor system energy use and half of all potential motor system energy savings. These groups include only 3,583 facilities, or 1.5 percent of all manufacturing plants.
- The largest 780 plants in the above groups account for over one-third of all manufacturing motor energy use. These plants are owned by roughly 500 separate companies.

Table E-4: Concentration of Motor Energy Use in Manufacturing

SIC Code	Industry Categories	Motor System Use (million kWh)	Percent of Total Manufacturing Motor System kWh	Motor System Savings (million kWh)	Number of Establishments
2621	Paper Mills	55,777	10.3%	5,711	310
2911	Petroleum Refining	40,805	7.5%	6,138	247
2819	Industrial Inorganic Chemicals, nec.*	37,232	6.9%	4,361	568
2631	Paperboard Mills	27,007	5.0%	2,765	219
3312	Blast Furnaces and Steel Mills	25,323	4.7%	2,742	284
2869	Industrial Organic Chemicals, nec.*	28,721	5.3%	3,364	631
2813	Industrial Gases	21,733	4.0%	2,545	623
2821	Plastics Materials and Resins	13,667	2.5%	1,601	456
3241	Cement, Hydraulic	9,147	1.7%	1,081	190
2611	Pulp Mills	6,402	1.2%	656	55
	Total of Top 10	265,814	49.1%	30,964	3,583
	Total: All Manufacturing	***541,203***		***62,350***	***246,950***

Sources: MECS 1994, Census of Manufactures 1992.
*nec. denotes “not elsewhere classified”.

For industries that use significant amounts of motor system energy, the financial impact of motor system energy costs and potential savings are substantial.

Table E-5 displays motor system energy use and potential savings per establishment in the 10 four-digit SIC groups with the highest annual motor energy consumption. In all these industries, the annual cost of motor system energy in a typical plant exceeds $1 million; in steel mills it is $6 million. Potential savings at the typical plant are also very large, ranging from $90,000 per year in the Industrial Organic Chemicals sector to nearly $1 million per year in petroleum refineries.

The right-hand column of Table E-5 shows potential energy savings as a percentage of operating margin. These figures suggest the potential impact of motor energy savings on the bottom line. The process industries listed in Table E-5 operate on very thin margins, that is: the difference between revenues from sales and variable costs including labor, materials, and selling costs. In 1996, operating margins for the 10 groups listed below ranged from 10 to 24 percent, and clustered around 16 percent. Thus, even relatively small increases in operating margin can have a significant impact on profitability.

A typical integrated steel mill spends about $6 million annually on motor system energy. One company—LTV Steel—is reducing its costs by improving this contact water system through the use of technologies such as ASDs and high efficiency pumps.

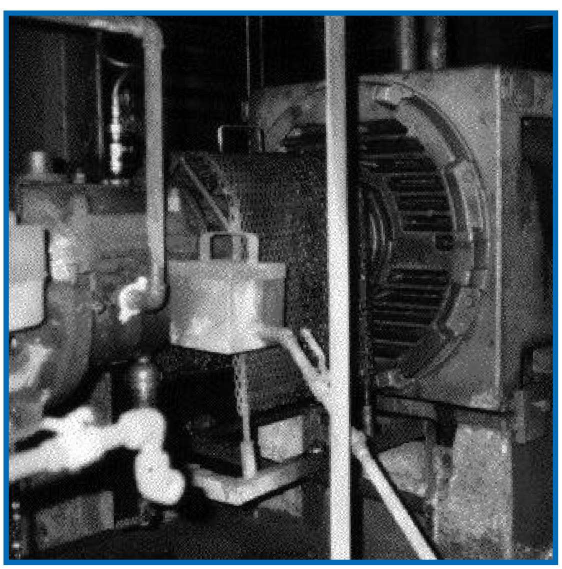


Table E-5: Financial Impact of Motor Energy Consumption and Savings: Selected Industries

Industry Groups	Motor System Costs/Estab.	Motor Energy Costs/Total Operating Costs	Savings per Estab. per Yr.	Savings as % of Operating Margin
Paper Mills	$4.6 mm	6.5%	$659,000	5.0%
Petroleum Refining	$5.6 mm	1.4%	$946,000	1.0%
Industrial Inorganic Chemicals, nec.	$1.6 mm	10.4%	$283,000	6.0%
Paperboard Mills	$3.0 mm	6.4%	$492,000	5.0%
Blast Furnaces and Steel Mills	$6.0 mm	2.1%	$358,000	2.0%
Industrial Organic Chemicals, nec.	$1.3 mm	1.0%	$91,000	1.0%
Industrial Gases	$1.1 mm	21.7%	$116,000	13.0%
Plastics Materials and Resins	$1.5 mm	1.5%	$121,000	1.0%
Cement, Hydraulic	$2.2 mm	9.6%	$219,000	4.0%
Pulp Mills	$1.7 mm	6.7%	$483,000	5.0%

Sources: MECS 1994, Bureau of Economic Analysis 1997, Census of Manufactures 1993.

The magnitude and patterns of motor system energy use and potential savings vary greatly among industries.

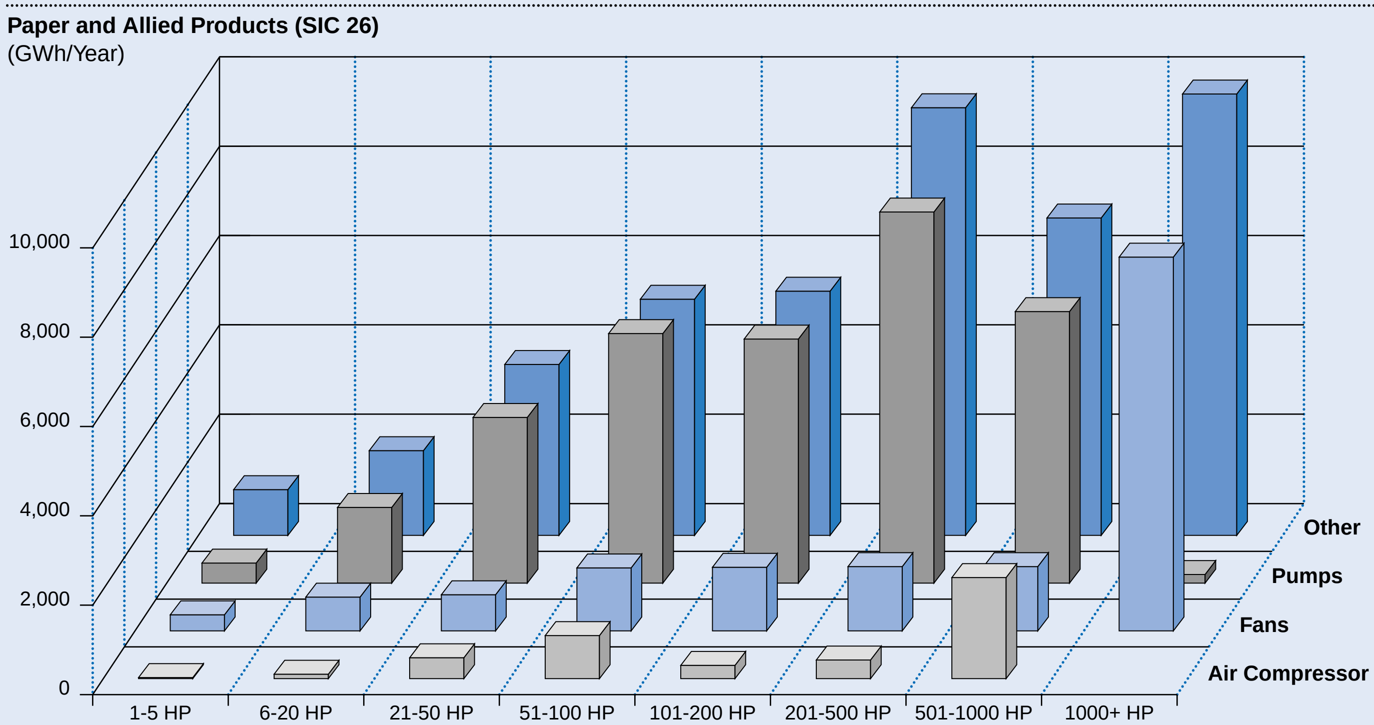
In developing motor systems efficiency strategies for individual plants or industries, it will be important to take these differences into account and to target sectors and measures with particularly high savings potential.

Patterns of motor energy use.
Each major industry group has a unique distribution of total motor system energy by application and motor size. Figure E-2 shows these distributions for the Paper and Allied Products (SIC 26) and Primary Metals (SIC 33) industries. Much of the motor system energy in the paper industry is concentrated in mid- and large-sized pumps, as well as in pulping equipment and paper machines which are driven, in part, by very large horsepower motors. In the metals industries, a great deal of motor system energy is concentrated in large fans which serve major combustion processes. Other concentrations of motor energy are in large air compressors and materials processing machines.

In Primary Metals, the largest savings are in large fan and air compressor systems. At Alcoa's Mount Holly aluminum production facility, the company managed to save more than $100,000 simply by shutting off one fan in each dust collection system.

Patterns of potential savings.
Figure E-3 shows that potential savings opportunities cluster in the application/horsepower groups with the greatest amounts of energy. Most of the savings in the paper industry are concentrated in improvements to pump systems. In Primary Metals, the largest savings can be found in large fan and air compressor systems. Savings in pump systems are also substantial in the lower horsepower ranges. The concentration of many of the savings opportunities in systems driven by large motors suggests that their implementation will require considerable planning and capital outlay.

Figure E-2: Motor System Energy Usage by Application and Motor Horsepower



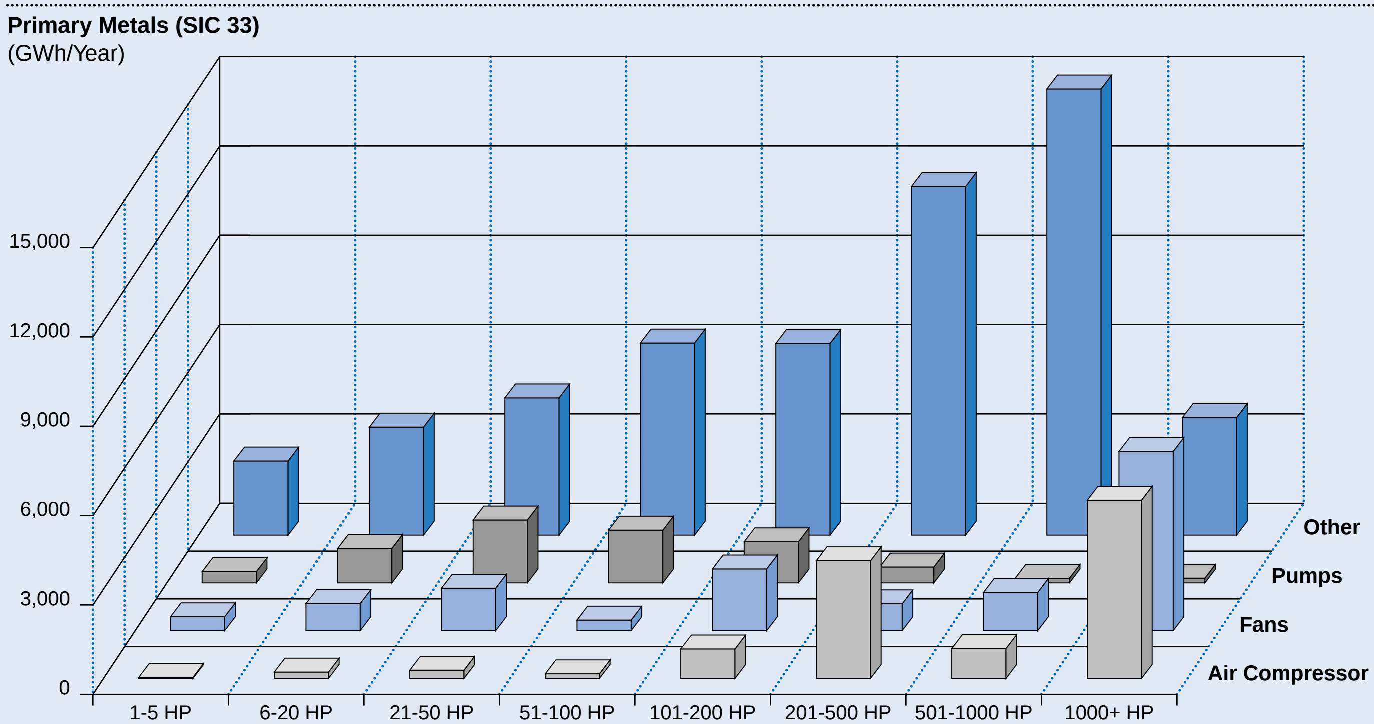
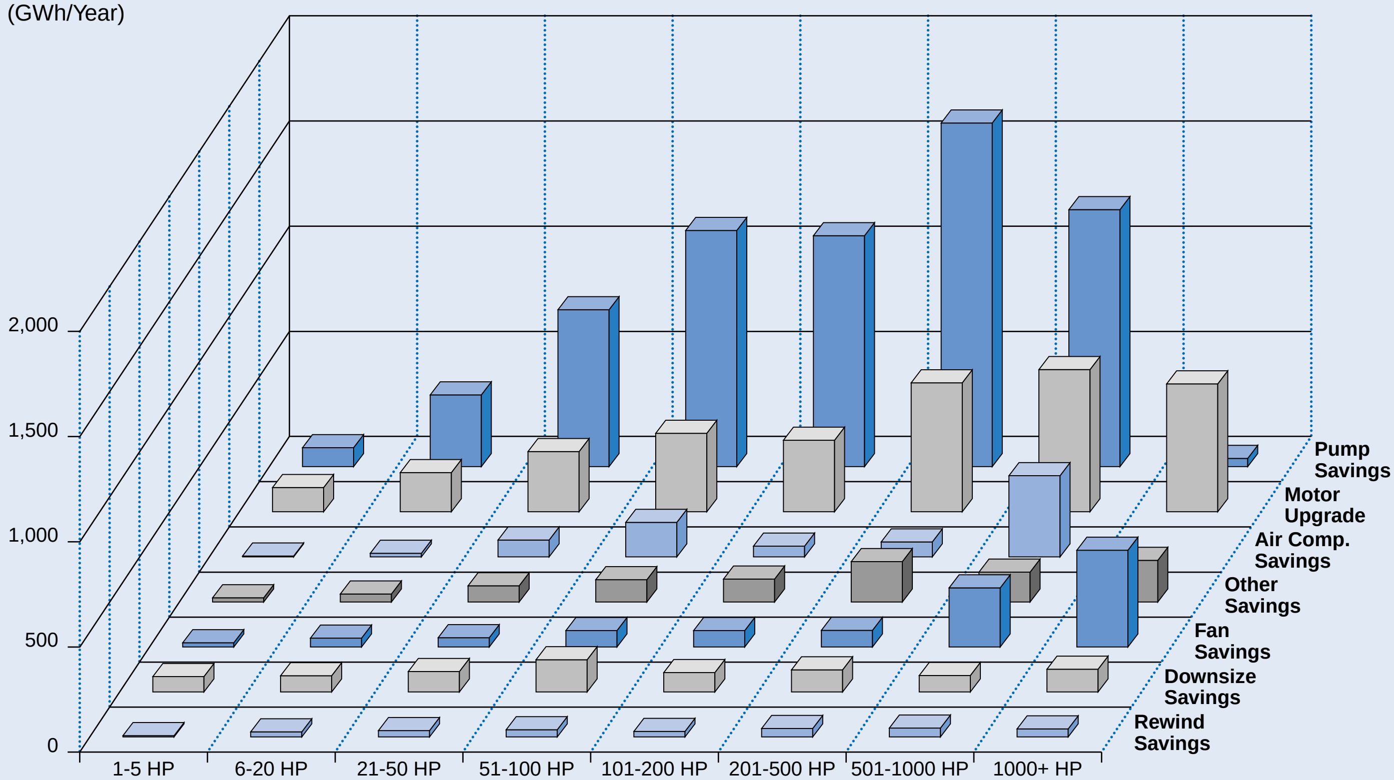
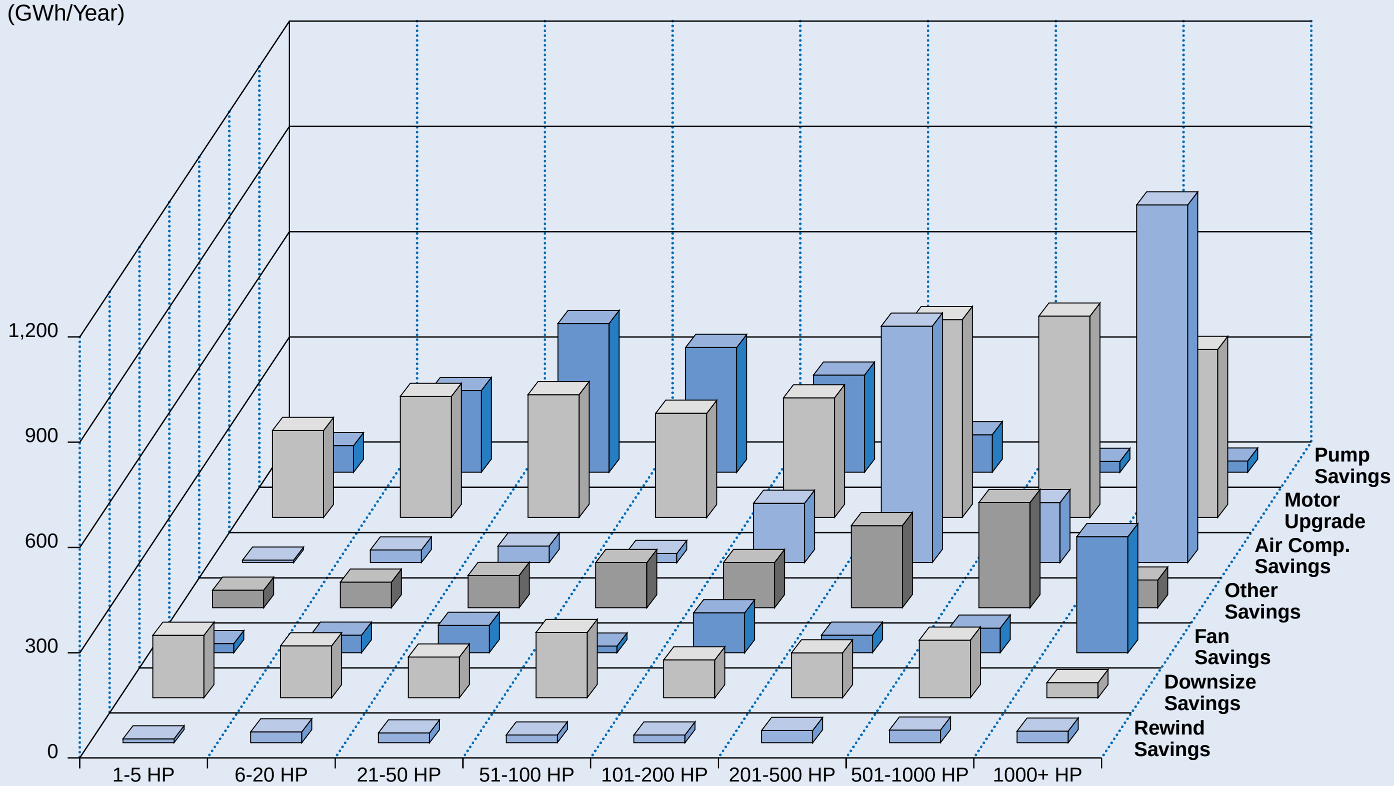


Figure E-3: Distribution of Potential Energy Savings by Application and Motor Size

Paper and Allied Products (SIC 26)
(GWh/Year)



Primary Metals (SIC 33)
(GWh/Year)



Patterns of potential savings across industries.
Table E-6 shows potential motor system energy savings by application for each two-digit SIC group. The numbers printed in blue indicate measure groups with particularly high concentrations of potential savings. These 22 SIC/measure groups (out of 126) account for 69 percent of all potential savings.

Table E-6: Potential Systems-Level Motor Energy Savings by Manufacturing SIC and Application

SIC	Industry Category	Estimated Savings (GWh/Year) Fan System	Pump System	Compressed Air Systems	Other Proc. Systems	Motor Upgrade	Motor Downsizing	Replace vs. Rewind	All Systems	As % of Total Energy
20	Food and Kindred Products	157	1,250	494	517	1,376	585	295	4,674	12.4%
21	Tobacco Products									
22	Textile Mill Products	170	593	408	166	743	305	121	2,506	15.0%
23	Apparel & Other Textile Products	1	0	68	15	47	22	8	162	13.9%
24	Lumber and Wood Products	153	243	324	341	432	336	184	2,013	8.8%
25	Furniture and Fixtures	87	5	78	33	173	68	26	471	12.7%
26	Paper and Allied Products	1,082	6,293	773	881	3,197	845	870	13,942	14.0%
27	Printing and Publishing	52	17	74	90	305	153	39	731	12.3%
28	Chemicals and Allied Products	942	7,556	6,813	994	4,219	1,409	1,255	23,188	16.1%
29	Petroleum and Coal Products	271	6,159	1,352	169	1,736	459	453	10,599	20.4%
30	Rubber and Misc. Plastics Products	113	1,851	813	411	1,498	435	303	5,424	14.8%
31	Leather and Leather Products	27	0	0	0	22	6	3	58	11.8%
32	Stone, Clay, and Glass Products	31	18	96	20	117	45	14	343	15.4%
33	Primary Metal Industries	738	1,537	2,150	1,085	3,199	983	749	10,441	11.9%
34	Fabricated Metal Products	34	181	303	80	298	195	46	1,137	15.6%
35	Industrial Machinery and Equipment	28	195	200	94	368	208	44	1,138	15.4%
36	Electronic and Other Electric Equipment	18	1,554	513	43	609	222	93	3,053	23.1%
37	Transportation Equipment	353	1,109	941	242	1,195	340	235	4,415	14.9%
38	Instruments and Related Products	71	119	123	78	263	169	39	862	13.3%
39	Misc. Manufacturing Industries									
	All Industry Groups	*4,330*	*28,681*	*15,524*	*5,259*	*19,799*	*6,786*	*4,778*	*85,157*	*14.8%*

Saturation of the most common motor system efficiency technologies—energy-efficient motors and adjustable speed drives—is relatively low.

- Energy-efficient motors. The inventory found that motors meeting EPAct standards accounted for 9.1 percent of all motors currently in use, with the highest concentration (25.5 percent) in the 101–200 horsepower range. EPAct compliant motors use 18.7 percent of total motor system energy in manufacturing.

- Adjustable speed drives. The inventory found that 9 percent of all observed motor systems, accounting for 4 percent of all motor system energy were equipped with adjustable speed drives. Over 90 percent of the ASD-equipped motor systems were of 20 horsepower or less. In this size range, it is more likely that the ASD was installed primarily to increase control over the production process rather than to save energy. Based on the application of engineering screening criteria for the application of ASDs, we estimate that motors representing 18 to 25 percent of total manufacturing motor system energy could be cost-effectively equipped with ASDs.

Over 40 percent of motors are operating at less than 40 percent part load. Substantial energy savings can be gained by better matching the size of the motor to the load.

Based on instantaneous load measurements of nearly 2,000 motors operating under reportedly normal conditions, we found that 44 percent were operating at part loads below their efficient operating range. We calculated energy savings associated with resizing these motors to better match load at 1.2 percent of total motor system energy. For pump, fan, and other fluid systems, low part loads may indicate that the entire system is operating at far below its optimal efficiency.

Except in the largest facilities, the level of knowledge and implementation of systematic approaches to motor system energy efficiency is low.

ELEMENTS OF BEST PRACTICE

Over the past 5 years, industrial engineers and plant managers have begun to evolve and articulate a systematic approach to achieving energy efficiency in motor systems. The development of this "systems approach" has been supported by Motor Challenge, as well as by dozens of efforts led by electric utilities, trade and professional organizations, and government agencies in the U.S. and Canada. The systems approach, as it now stands, consists of three elements:

- System performance optimization;
- Selection of efficient components; and
- Operation and maintenance.

Table E-7 provides examples of each of these elements in the context of pumping systems, along with the range of savings associated with each kind of efficiency measure. Similar tables for other kinds of fluid systems are found in Section 2 of this report.

Table E-7: Energy Saving Opportunities in Pump Systems

Equipment Group/Efficiency Measure	Range of Savings (Percent of System Energy)
Process System Design	
Reduce Overall System Requirements	
•Equalize flow over production cycle using holding tanks.	10%–20%: depends on variation in flow.
•Eliminate bypass loops and other unnecessary flows.	10%–20%: depends on initial system design.
•Increase piping diameter to reduce friction.	5%–20%: depends on initial system design.
•Reduce "safety margins" in design system capacity.	5%–10%
•Reduce system effects due to piping bends.	
Match Pump Size to Load	
•Install parallel systems for highly variable loads.	10%-30%: depends on initial system design.
Reduce or Control Pump Speed	
•Reduce speed for fixed loads: trim impeller, lower gear ratios.	5%–40%: depends on initial system design.
•Replace throttling valves with speed controls to meet variable loads.	5%–50%: depends on initial system design.
Component Purchase	
•Replace typical pump with most efficient model.	1%–2%
•Replace belt drives with direct coupling.	About 1%
•Replace typical motor with most efficient model.	1%–3%
Operation and Maintenance	
•Replace worn impellers, especially in caustic or semi-solid applications.	1%–5%

FINDINGS ON CURRENT MOTOR SYSTEMS DESIGN, PURCHASE, AND MAINTENANCE PRACTICES

The following paragraphs summarize key findings on customers' awareness and implementation of the elements of best practice discussed above. Percentages reflect weighting of Practices Inventory results to the population.

- Most motor purchase decisions are made at the plant level. Even among multi-site organizations, 91 percent reported that all motor purchase decisions were made at the plant level.

- Awareness of the availability of energy-efficient motors and understanding of their performance advantages is low. Only 19 percent of respondents reported being aware of "premium efficiency" motors, the common marketing designation for motors that met EPAct standards prior to their promulgation in October 1997.

  Only 4 percent of customers reported that they understood the efficiency ratings associated with the premium or high-efficiency designations; 38 percent reported being somewhat aware of these relationships. These results likely reflect the inconsistency of product designations that existed prior to the promulgation of the EPAct standards, as well as generally low levels of product knowledge.

Motor purchase decisions are typically made at the plant level.

- Only 22 percent of customers surveyed reported that they had purchased any efficient motors in the past year. Among all customers surveyed, the average reported percentage of efficient motors purchased in the past year was 12 percent. According to the Bureau of the Census *Current Industrial Reports,* efficient motors constituted 15 percent of all 1–200 horsepower units shipped domestically in 1996. Thus we believe that customer reporting on this topic was fairly accurate.

- Customers most often use the size of the failed motor being replaced as a key factor in selecting the size of the new motor. Twenty-nine percent use the size of the failed motor as the *only* factor in the sizing decision. This practice can lead to persistent oversizing of motors, which leads to inefficient operations.

- Only 11 percent of customers interviewed reported having written specifications for motor purchases; only two-thirds of these customers included efficiency in their specifications. Consistent with other findings, larger plants tended to use written specifications more often than smaller ones.

- Reducing capital costs is the most important consideration driving customers' decision whether to rewind or replace failed motors. Only 12 percent of customers reported that they considered the lower energy operating costs of new motors in the rewind versus replace decisions. Very few customers report providing specifications to rewind contractors. If improperly done, rewinding reduces the efficiency of motors from 1 to 2 percent.

- Except among the very largest facilities, the frequency with which system-level improvements are undertaken is very low. Customers were asked whether they had implemented a list of specific system-level improvements for pump, fan, and compressed air systems over the past 2 years. Except for fixing leaks in compressed air systems, none of the measures were mentioned by more than 8 percent of the respondents. Larger facilities reported making such improvements more frequently.

See Table E-8 for a summary of these results.

Table E-8: Reported System Measures Undertaken During the 2 Years Prior to the Inventory

	Size Categories[5]					
	Large	**Med/Large**	**Medium**	**Sm/Med**	**Small**	***Total***
Fan Systems						
Retrofitted with ASDs	20%	7%	1%	0%	1%	***1%***
Retrofitted with inlet guide vanes	9%	1%	0%	0%	3%	***2%***
Checked components with large pressure drops	3%	1%	10%	0%	3%	***3%***
No fan systems in facility	0%	29%	24%	18%	43%	***38%***
No improvements	67%	49%	45%	80%	33%	***40%***
Pump Systems						
Substituted speed controls for throttling	22%	8%	11%	1%	0%	***1%***
Used parallel pumps to respond to variations in load	14%	4%	2%	0%	3%	***2%***
Reduced pump size to fit load	0%	5%	7%	11%	3%	***4%***
Increased pipe diameter to reduce friction	5%	6%	6%	11%	1%	***3%***
No pump systems in facility	13%	28%	24%	17%	40%	***35%***
No improvements	45%	57%	42%	52%	34%	***38%***
Compressed Air Systems						
Replaced 1-stage rotary screw units with more efficient models	7%	16%	29%	2%	4%	***6%***
Used parallel compressors to respond to variations in load	23%	12%	10%	13%	7%	***8%***
Reconfigured piping and filters to reduce pressure drops	14%	24%	5%	13%	1%	***5%***
Added multi-unit controls to reduce part load consumption	23%	10%	6%	0%	4%	***4%***
Reduced size of compressors to better match load	10%	6%	1%	2%	1%	***1%***
Fixed leaks	42%	40%	34%	36%	15%	***20%***
No compressed air systems in facility	0%	3%	0%	1%	10%	***8%***
No improvements	39%	44%	37%	62%	52%	***52%***
No Reported Improvements	30%	27%	14%	45%	21%	***24%***

[5] The size categories are based on sample stratification cut points. All establishments in each two-digit SIC group were initially allocated to Large, Medium, and Small size strata, with roughly one-third of all establishments in the SIC group in each size stratum. The cut points between Large, Medium, and Small varied by SIC group. In some regions, we needed to combine adjacent groups to provide a sufficiently large sample frame. Thus, Large and Medium/Large are not mutually exclusive size designations. Likewise for Small and Medium/Small.

ORGANIZATION OF THE REPORT

The remainder of this report is organized as follows:

- Section 1: The U.S. Industrial Motor Systems Inventory. This section presents the results of the Inventory, focusing on the distribution of manufacturing motor systems and energy by industry, horsepower, application, efficiency, hours of use, and part load. This section also contains case studies of motor system energy use in non-manufacturing industries.
- Section 2: Motor System Energy Savings Opportunities. This section presents detailed estimates of motor system energy savings by type of measure, industry, application, and horsepower size. We also provide extensive documentation of the methods used to develop these estimates.
- Section 3: Motor Systems Purchase and Maintenance Practices. This section presents the results of the Practices Inventory in detail, along with related information from the literature.
- Appendix A: Profiles of Key Industrial Sectors contains short profiles of five key motor system energy-using sectors covering industry structure and conditions, general energy use patterns, and technical energy savings opportunities specific to the industry. Appendix A also includes summaries of inventories performed at non-manufacturing industrial sites.
- Appendix B: Standard Tables contains detailed tables of motor inventory and savings information for each two-digit manufacturing SIC group.
- Appendix C: Methodology contains detailed technical descriptions of the sampling approach and variance calculations. It also contains copies of data collection forms.
- Appendix D: Stock Adjustment Model contains a description of the model used to forecast the size and overall efficiency of the manufacturing motor inventory. It also contains the inputs, assumptions, and results of the forecast through the year 2002.

Section 1: The U.S. Industrial Motor Systems Inventory

INTRODUCTION

This section presents the methods and key results of the inventory study. We begin with a brief description of the sampling and data collection methods we used to develop the inventory database.[1] The section continues with a comparison of the methods used in this study to methods used in other characterizations of the industrial motor systems population and energy use. This comparison clarifies the most appropriate uses of this and other studies, as well as limitations on their interpretation. We conclude with the findings from the inventory itself.

RESEARCH METHODS

OBJECTIVES

Overall, the objectives of the MAI were to:

- Characterize motor systems and the energy they use for all major manufacturing groups (SICs 20–39) and selected non-manufacturing industries. In particular, estimate the distribution of the population on key attributes that affect energy consumption and potential savings: horsepower, type of motor, application, part load, hours of application, and nominal efficiency.
- Characterize the extent to which energy savings opportunities are present in the motor systems inventory and estimate potential energy savings associated with those opportunities—again for each major industry group.
- Characterize the procedures that facilities managers use to purchase, manage, and maintain motor systems, as well as their awareness, knowledge, and adoption of specific measures to reduce motor system energy use.

To our knowledge, the *U.S. Industrial Electric Motor Systems Market Opportunities Assessment* is the only study ever undertaken with the specific objective of characterizing the population of motor systems in manufacturing for any geographic area—much less for the country as a whole—using direct observations of a representative sample of facilities.[2]

We faced two key methodological challenges in achieving the study's objectives. These were:

- Develop a sampling approach which would enable us to characterize the highly diverse population of manufacturing plants based on a relatively small number of observations.
- Develop an on-site data collection protocol which would enable us to collect detailed information on every motor system within a factory (or a large sample of motors in big plants) without overburdening the participating companies.

The paragraphs below describe how we addressed these challenges. We conclude this section with a brief description of how the inventory was actually conducted, the disposition of the sample, and some of the practical difficulties we encountered.

1 For a more technical description of survey methods, see Appendix C: Methodology, which contains detailed descriptions of our sampling approach, sample disposition, and variance calculations. Appendix C also contains copies of all data collection forms and field descriptions.

2 A number of utilities have undertaken audits of representative samples of industrial facilities in their service territories that have included inventories of electric motors. For descriptions and results of these studies, see the *Interim Report* of this project.

SAMPLING APPROACH

SCOPE: DEFINITION OF STUDY POPULATION

Industries covered.
Initially, DOE specified the scope of the study to include all manufacturing industries (SICs 20–39) as well as selected non-manufacturing industries: mining, agriculture, water supply, irrigation, wastewater treatment, and oil and gas extraction. Early in the project, we determined that it would be possible to complete roughly 300 site inventories of sufficient detail to meet the project's analytical objectives, given the budget and schedule. We further determined it would not be feasible to characterize all of the manufacturing and non-manufacturing facilities in the population on the basis of a sample of 300. We decided, in consultation with DOE, to allocate as much of the sample to the manufacturing industries as would be necessary to develop reasonably precise estimates of their characteristics. The remaining sample would be allocated to the non-manufacturing industries, with the resulting observations to be treated essentially as case studies. Ultimately, 30 sample slots were set aside for non-manufacturing sites.

The sampling plan described below pertains to *manufacturing facilities only.* However, we used the same data collection protocol for all sites.

Motor system applications covered.
All motor systems associated with production activities were included in the universe. Motors associated with boilers and compressors which provided process heat and cooling were included in the inventory. Motors associated solely with plant heating and ventilating equipment were not.

Motor sizes covered.
Only systems driven by integral horsepower motors (1 HP or greater) were included in the inventory.

SAMPLE DESIGN: GENERAL APPROACH

The general strategy for the sample allocation was to select sites with probability proportional to size. That is, the chance that a particular site would be selected into the sample was proportional to its size. Larger sites have a higher chance of being in the sample, and smaller sites have a lower chance. Thus, for any subset of the population, the investment in data collection for that subset and the amount of information collected is roughly proportional to the size of the subset. Those groups that account for the most motor system energy consumption, and the most site-to-site variability, have the best information collected and tend to be the most accurately characterized; those that account for the least consumption have the least information and are least accurately characterized.

SAMPLE FRAME

We used the *iMarket MarketPlace* Dun & Bradstreet database as the sample frame—that is, the list of all industrial facilities that constituted the population for the study. The MarketPlace database contains records from all establishments identified through Dun & Bradstreet's credit rating service. The number and distribution of establishments by SIC code in this database are fairly similar to those found by the Census of Manufacturers for companies with 20 or more employees.

The MarketPlace database identifies several key pieces of information for each facility, including: primary SIC code; sales volume; employment; geographic location using the Bureau of the Census metropolitan statistical areas (MSAs); contact information; and whether manufacturing is actually conducted at the site.[3]

MEASURE OF SIZE

We used facility employment as recorded in Dun & Bradstreet as the basis for characterizing sites by size. However, motor system energy use per employee differs greatly among SIC groups. As Table 1-1 shows, annual motor system energy use per employee ranges from 3,593 kWh in Apparel and Other Textile Products (SIC 23) to 402,434 in Petroleum and Coal Products (SIC 29). To develop a meaningful measure of size for allocating the sample, we needed to translate the employment for each site into a preliminary estimate of motor energy use. To do so, we used an estimated motor energy use per employee specific to each SIC developed from the results of the 1991 Manufacturing Energy Consumption Survey (MECS)[4], a national survey of manufacturing energy use and related information sponsored by the Energy Information Administration (EIA). These factors were applied to site-level employment data from the Dun & Bradstreet database to estimate the motor system energy consumption of sites or groups of sites for use in sampling.

Table 1-1: Motor System Energy Use per Employee in Manufacturing

SIC Number	Industry Description	Motor System kWh per Year per Employee
20	Food and Kindred Products	31,229
21	Tobacco Products	29,323
22	Textile Mill Products	36,267
23	Apparel and Other Textile Products	3,593
24	Lumber and Wood Products	21,095
25	Furniture and Fixtures	7,111
26	Paper and Allied Products	157,448
27	Printing and Publishing	5,657
28	Chemicals and Allied Products	164,464
29	Petroleum and Coal Products	402,434
30	Rubber and Miscellaneous Plastics Products	25,456
31	Leather and Leather Products	6,623
32	Stone, Clay, and Glass Products	42,894
33	Primary Metal Industries	66,996
34	Fabricated Metal Products	11,939
35	Industrial Machinery and Equipment	7,589
36	Electronic and Other Electric Equipment	7,453
37	Transportation Equipment	11,787
38	Instruments and Related Products	5,822
39	Miscellaneous Manufacturing Industries	5,887
	Manufacturing Average	***31,233***

Source: MECS, 1994, Energy Information Administration (EIA).

[3] Metropolitan Statistical Areas (MSAs) are geographic subdivisions established by the Bureau of the Census to organize data collection. In most states, they correspond to the larger cities and counties in which they are located. In the Northeast, where political subdivisions are more irregular, MSAs may contain more than one county or portions of counties, as well as their central city.

[4] Results of the 1994 MECS were not available at the time the sample was developed.

FURTHER REFINEMENTS TO SAMPLE FRAME

In our initial work on the sample, we made a number of refinements to limit the sample frame so that it matched the objectives and resources of the project. We defined our frame as all Dun & Bradstreet listings in the target SIC groups that had manufacturing activity present at the site. The target SIC groups were the 20 manufacturing two-digit SIC groups, SIC codes 20 through 39. We further restricted our frame to the top 174 (out of 324) MSAs in terms of estimated motor system energy use.

The 174 MSAs included in the sampling frame accounted for 91.7 percent of the estimated manufacturing motor energy use for all MSAs and 72.1 percent of the estimated manufacturing motor energy use for the entire U.S. The second percentage is lower because not all manufacturing facilities are located in MSAs. For example, many pulp and paper mills and primary metal factories are located in rural areas near the natural resources that supply them. We developed a separate process to select a sample of facilities that are located outside MSAs.

SAMPLE STRATIFICATION

The total sample was stratified on three variables:

- Geographic location. Geographic stratification was required to ensure that the sample was geographically dispersed for a good representation across the country. Geographic clustering was required to contain field costs.
- Industry type (SIC). The sample was stratified by two-digit SIC to ensure a minimum coverage of each manufacturing SIC. In addition, under the probability-proportional-to-size approach, different SICs were sampled at a higher rate because of their greater motor energy use.
- Size of facility. The sample was stratified by size as the basis for the sampling with probability in proportion to size. For the main sample, each SIC group was divided into large, medium, and small size strata based on the distribution of total employment among all the establishments in the SIC. The general approach was to split each SIC into three size groups, each accounting for about one-third of the total employment. The break points for the three size strata were therefore defined differently for each SIC.

SAMPLE ALLOCATION AND SELECTION

The sample was designed to cover all manufacturing SICs, all regions of the country, and all sizes of operations. To control field costs, it was necessary to limit the data collection to approximately 20 geographic areas. To cover all these factors and use the sample resources efficiently, sample design and selection proceeded through the following stages:

- Allocation of the overall manufacturing sample to sites within and outside MSAs.
- Allocation of the manufacturing samples to geographic areas (Primary Sampling Units or PSUs).
- Allocation of the PSU samples to cells defined by SIC code and size.
- Random selection of sites that fell into the selected sample cells defined by PSU, SIC, and size.

At each stage the selection of PSUs and sample cells and the allocation of the final sample to the sample cells were accomplished using methods based on probability proportional to size. See Appendix C for more detail on the sample design and allocation procedures. Figure 1-1 shows the distribution of completed inventories by PSU. Table 1-2 shows the distribution of the

Figure 1-1: Locations of Completed Inventories (PSU)

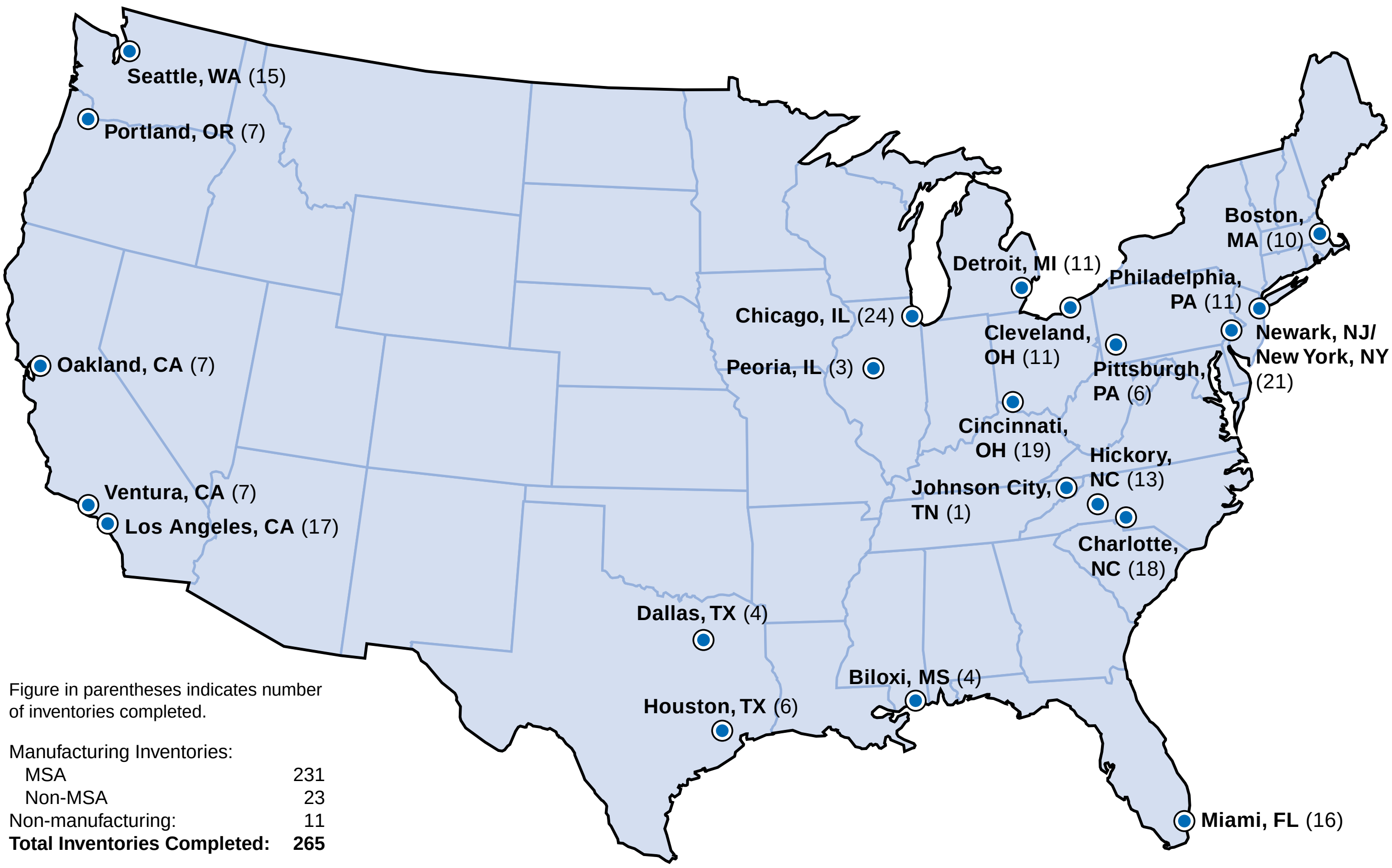


Figure in parentheses indicates number of inventories completed.

Manufacturing Inventories:	
MSA	231
Non-MSA	23
Non-manufacturing:	11
Total Inventories Completed:	**265**

completed inventories by SIC and size category. In interpreting Table 1-2, readers should keep in mind the following concerning size categories:

- For purposes of the initial sample development, there were only three size categories: Small, Medium, and Large. The break points between these three categories were set individually for each two-digit manufacturing group. The criterion in setting the break point was to allocate roughly equal portions of total estimated motor system energy (from MECS) to each of the strata. This is a typical procedure used to minimize the variance of estimates and to simplify variance calculations.

- The Small/Medium and Medium/Large categories represent combinations of the two strata rather than a unique group that falls in between the two. For some SIC/PSU combinations, it was necessary to combine size categories in order to have enough facilities to provide the requisite number of completed inventories, after taking sample attrition and refusals into account.

The two right-hand columns of Table 1-2 present a comparison of the distribution of the manufacturing sample to the manufacturing SIC groups versus the distribution of motor system energy to SIC groups provided in MECS. These distributions resemble each other quite closely.

Table 1-2: Distribution of Completed Inventories by SIC and Size

SIC Group	Size Strata* S	S/M	M	M/L	L	Total	% of Completed Inventories	% of Total MECS Motor Energy
20 Food	2	2	0	12	2	18	7.1%	8.8%
21 Tobacco						0	0.0%	0.2%
22 Textile	4	1	2	3	2	12	4.7%	3.9%
23 Apparel	2	0	0	2	0	4	1.6%	0.6%
24 Lumber	3	2	1	4	2	12	4.7%	2.9%
25 Furniture	1	0	1	2	1	5	2.0%	0.7%
26 Paper	14	2	6	14	3	39	15.4%	18.4%
27 Printing	3	0	0	3	0	6	2.4%	1.6%
28 Chemicals	8	5	6	26	5	50	19.7%	25.0%
29 Petroleum	6	11	0	6	1	24	9.4%	7.9%
30 Rubber	8	0	4	4	4	20	7.9%	4.8%
31 Leather	1	0	0	0	0	1	0.4%	0.1%
32 Stone	2	0	0	4	0	6	2.4%	4.1%
33 Metal	8	4	0	11	0	23	9.1%	8.5%
34 Fabricated Metal	3	0	5	2	0	10	3.9%	3.3%
35 Machinery	3	0	2	1	0	6	2.4%	2.8%
36 Electric	1	0	2	2	0	5	2.0%	2.1%
37 Transportation	2	1	0	2	2	7	2.8%	3.2%
38 Instruments	2	2	0	2	0	6	2.4%	0.9%
39 Miscellaneous						0	0.0%	0.4%
Total Manufacturing	***73***	***30***	***29***	***100***	***22***	***254***		
Non-manufacturing Inventories								
02 Agriculture						2		
12 Metal Mining						1		
13 Oil & Gas Extraction						1		
14 Mineral Mining						2		
49 Water & Wastewater						5		
Total Non-manufacturing						***11***		
Total Inventories						***265***		

*The Large and Medium strata were combined in some region/SIC groups to form the Large/Medium stratum. The same procedure was used in regard to the Small/Medium stratum. See pp. 1-6 and App. C for more on this topic.

DATA COLLECTION METHODS

Once a site was selected into the sample, data collection proceeded in the following stages:

- Recruitment and collection of pre-contact data. Trained schedulers initiated contact with the selected facility over the phone. The first objective of the call was to determine whether the site was eligible to be included in the inventory. To be eligible, the site needed to meet the following criteria: (1) use integral horsepower motors in its production facilities; and (2) be correctly classified as to two-digit SIC by Dun & Bradstreet. Once we determined that these criteria were met, we went on to solicit the facility's participation in the inventory and gather information to facilitate scheduling.

To encourage participation, we offered facilities a report of the motor inventory, a copy of the MotorMaster+ software, and an electronic data base of the motor inventory entered into that software. We also provided a MotorMaster+ report that identified specific motors that can be cost-effectively upgraded to a higher efficiency.

Each audit was carried out by one field engineer who had participated in extensive classroom and field training. The field engineers required an escort in the facility. Based on experience with similar surveys, we determined that three days was the maximum plant staff would agree to have us on site. The data collection protocol was designed so that it could be completed in three days, even in large sites.

Initial interview and Practices Inventory. The field engineer's first task upon arriving on site was to complete the Practices Inventory with the principal contact. This was generally the maintenance manager, plant engineer, or, in smaller facilities, the owner. Table 1-3 shows the topics covered and the analyses supported by the Practices Inventory.

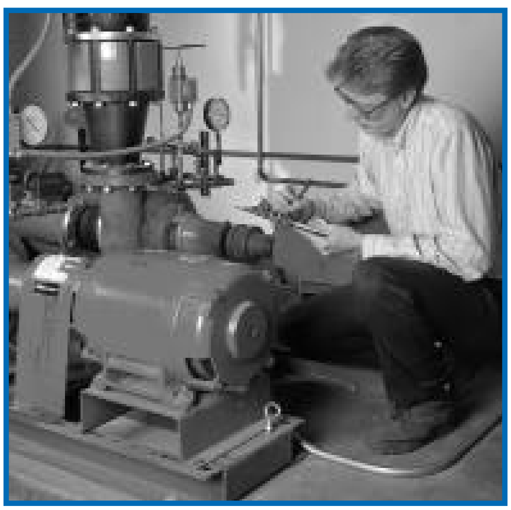
Table 1-3: Topics Covered and Analyses Supported by the Practices Inventory

Topics Covered	Analyses Supported
• Inventory adjustment variables: rates of failure; rewinding and repair; replacement; scrappage and second-hand sales. • Factors affecting the rewind/replace decision. • Criteria applied for selecting energy-efficient motors. • Use and nature of specifications in motor purchase and rewind situations. • Description of maintenance practices. • Purchasing and maintenance practices for generic equipment: pumps, fans, compressors.	• Estimate prevalence of "best practices" in motor purchasing and maintenance. • Identify opportunities to save energy by providing information and education. • Establish baseline practices for use in analysis of Motor Challenge effects. • Estimate parameters for a stock adjustment model to translate data on motor shipments into changes in inventory.

At this stage, the field engineer also collected information on a variety of other topics including: facility electric use; identification of key processes; identification of production departments; and a rough allocation of total facility motor energy use to the different departments.

Motor Inventory. After the initial interview and Practices Inventory, the field engineer made a quick walkthrough inspection of the facility accompanied by an escort. The objectives of the walkthrough were to confirm the rough allocation of motor energy to the departments and to map out a strategy for accomplishing the data collection as quickly as possible. For large sites which could not be fully inventoried in three days (over 300 motor systems), there was a second objective. This was to work out the application of prescribed methods for sampling motors within the site. This method is described in Appendix C. During the walkthrough, the field engineer also collected data at the department level—primarily hours of operation.

For this inventory, field engineers collected data on motor systems in 254 manufacturing plants.



Jeff Uhrlaub, Uhrlaub Photography

Once the field engineer determined the best general approach to the site, he collected information on all motor systems in the plant, or within the sampled areas. Table 1-4 shows the individual pieces of inventory data which were collected at the site, department, and individual motor system levels. For purposes of data collection, the motor system consisted of the motor itself, controls on the immediate motor circuit, the drive train, and speed controls.

Instantaneous load measurements. Once the inventory was completed, the field engineer took instantaneous load measurements on a sample of 12 operating motors within the plant. The measurements were made using the two-wattmeter method. The method used to select the sample of motor systems to be metered is described in Appendix C.

SAMPLING WITHIN SITES

Sampling the inventory in large sites.
Based on field tests of the data collection methods, we determined that a field engineer could inventory a maximum of 300 motor systems during a 3-day visit. We knew that many of the sample facilities would have more than 300 motors. Some would have thousands. To address this situation, we developed a procedure to select a representative sample of motors in the large sites. The challenge in these cases was that, in all but one or two exceptional factories that kept complete motor inventories, we had no list of motors to start from. Thus, our sampling approach proceeded in the following steps:

- Divide the facility into logically grouped areas, using the experience of the escort as a guide.
- Estimate the percentage of total motor energy accounted for by each logical division, again relying on site personnel. This factor was used in weighting the results.
- Select areas of the plant for inclusion in the inventory using random procedures.
- Complete full motor system inventories of the selected areas.

Of the 254 manufacturing sites inventoried, 86, or 33.8 percent used this sampling approach to complete the motor systems inventory.

Table 1-4: Overview of Field Data Collection for the Inventory

Level of Observation/Type of Data
Facility Level Observations • Number of employees • Total electric consumption and costs • List of principal industrial processes in the plant • Size of the plant and production areas
Department Level Observations • Operating schedules • Estimated percentage of total plant motor energy (where internal sampling was needed)
Motor System Level: Component Data • Component type: e.g., pump, fan, air compressor, refrigeration compressor, etc. • Process: e.g., grinding, gas separation, process heat, etc. • Component age • Load modulation type: e.g., throttle valve, ASD, inlet vane, outlet damper, mechanical clutch • Mechanical drive type: e.g., shaft, flat belt, V-belt, roller chain, etc. • Manufacturer • Escort’s assessment of whether the load is fluctuating or constant • Diversity: i.e., percentage of department operating hours the motor is on, per escort
Motor Data • Size (HP or KW converted to HP) • NEMA design: A, B, C, D, E, DC motor; synchronous motor; or other special purpose • Motor age • Synchronous speed • Enclosure type • Voltage rating and “wired for” voltage • Manufacturer • Nameplate speed • Nameplate amps • Nameplate power factor • Nameplate efficiency

Selection of motors for load measurement.

We selected motors for load measurement by making random selections from the list of motors inventoried. The quotas for size categories were developed based on information on the allocation of motor energy developed for the larger sampling effort. The quotas were as follows: in 1–19 horsepower, it was three motors; in 20–29 horsepower, it was four motors; and in 100+ horsepower, it was five motors. If there were fewer motors in the higher HP categories than the quota required, the remaining samples were allocated to the next lowest size category. Thus, if a plant had only two motors of 100 horsepower or more, the allocation would be: 1–19 HP: three motors; 20–99 HP: seven motors; 100+ HP: two motors.

INVENTORY ADMINISTRATION AND RESPONSE

We tested the data collection protocol at a number of sites in the late summer and autumn of 1996. Based on this work, we refined the data collection protocol and solicitation system substantially. Field engineers were recruited and trained in November and December of 1996, and field work began in earnest in January 1997. It took approximately 10 months to complete the data collection.

Convincing facility owners and managers to allow us to conduct the inventory at their plants proved to be the most difficult part of the inventory. We recruited participants essentially through “cold calling.” The process of identifying the appropriate decision maker and gaining their permission took an average of four to six telephone calls and fax communications.

Table 1-5 shows the results of our sample recruitment efforts. We attempted to contact nearly 4,500 facilities listed in the Dun & Bradstreet database. We determined that 8.4 percent of these facilities did not exist, and we were unable to establish contact with a similar number. Among those we were able to contact, nearly half refused to take part in the inventory. Another sizable portion deferred their decision for so long that their sample cell was closed before they replied. These can be interpreted as polite refusals. We also determined that roughly one-quarter of the facilities we attempted to contact fell out of the scope of the study. Among the typical reasons for disqualification: there were no integral horsepower motors on site; no manufacturing activities were conducted at the site; Dun & Bradstreet had misclassified the site in terms of SIC or size. The information gained from the screening calls was used in developing the results of the inventory. For more on this topic, see Appendix C.

We obtained initial permission to undertake the inventory from 277, or 6.3 percent of those contacted. Twenty-three of these customers later declined to be inventoried. We had similar success in lining up non-manufacturing sites. Larger facilities were more likely than others to participate in the inventory. Among companies in the Large and Medium/Large strata, participation rates averaged 17 percent, versus the 6 percent for the inventory as a whole. This pattern is not surprising for a number of reasons. First, larger facilities had more to gain from products we offered in exchange for their cooperation, since they had more motor systems on site. Second, larger facilities generally had more personnel to assign to escorting the field engineer and taking load measurement readings. Many smaller companies did not have electricians on staff. The understaffing of the maintenance function, which we observed throughout the sample, was particularly pronounced for smaller companies. Once the field engineers were on site, however, they enjoyed a very high level of cooperation and response from their hosts.

Table 1-5: Disposition of Manufacturing Sample

Disposition	Number	% of Sites Attempted
Complete	254	5.7%
Canceled	23	0.5%
Does not Exist	375	8.4%
Refused/Not Interested	1,730	38.7%
Not Qualified	1,057	23.7%
Not Contacted	378	8.5%
Decision Pending when Quota Filled	651	14.6%
Total	***4,468***	***100.0%***

THE MARKET ASSESSMENT INVENTORY IN THE CONTEXT OF PREVIOUS STUDIES: APPROPRIATE APPLICATIONS AND CAVEATS

Over the past decade, analysts of the market for industrial motor systems have relied primarily on two sets of sources to characterize the inventory. The first is the Manufacturing Energy Consumption Survey (MECS), a triennial survey of over 15,000 manufacturing establishments designed to estimate the amount of different kinds of energy used at very fine levels of industry and geographic aggregation. The second is a series of market research studies based on a combination of expert industry opinion, shipment data, and a variety of secondary sources. The earliest of these studies was conducted by Arthur D. Little for DOE in 1977 and revised in 1980. Succeeding studies in this vein have essentially been updates of the Arthur D. Little work. Readers wishing to get the maximum value from these sources, as well as from the MAI, should be acquainted with their strengths and limitations. In this section, we briefly describe the MECS and the market research studies, and compare their outputs and appropriate applications with those of this study.

THE MANUFACTURING ENERGY CONSUMPTION SURVEY (MECS)

MECS is a survey of roughly 15,000 industrial facilities drawn from the Census of Manufactures sample frame. MECS is conducted every 3 years. The most recent survey for which results are now available was completed in 1994.

MECS is designed and analyzed by the Energy Information Agency and administered by the Bureau of the Census. The survey's principal objective is to estimate consumption of various forms of energy by the population of facilities in all manufacturing industries (SICs 20–39). Respondents to the survey compile energy bills and report total consumption of electricity and other fuels for the calendar year preceding the survey. When combined with information on the facility such as value of shipments, value added, and employment, the fuel consumption data provide much useful information on energy use in individual industries, as well as ratios by which meaningful comparisons can be made between industries.

The survey's sampling methods are rigorous, and it enjoys the benefit of access to the Census of Manufacturers' sample frame and sampling apparatus. Moreover, the survey has enjoyed extremely high levels of customers response—90 percent in the most recent rounds. These procedures and response levels ensure the representativeness of the results.

Perhaps most important for this project, MECS estimates the proportion of total electricity used by motor systems in industrial processes by industry for all two-digit SICs, and selected three and four-digit SICs. This allocation is based on the respondent's estimate of the allocation of total electric consumption among end uses. The process related end-use categories to which respondents may allocate electricity usage are: Process Heating, Process Cooling and Refrigeration, Machine Drive, Electro-Chemical Processes, and Other Process Uses. The sum of electricity in the Machine Drive and Process Cooling and Refrigeration categories corresponds to the energy the MAI was designed to estimate.[5]

Generally, an individual familiar with plant operations answers the questions concerning the allocation of energy to end uses.[6] However, the survey form itself offers no guidance on how to make this allocation, beyond providing a few examples of the kinds of end uses included in the larger categories. At no point in the survey are the end-use allocations corroborated by any kind of field observation.

Strengths of the MECS estimates.
The strengths of MECS as a source on motor system energy can be summarized as follows:

- It is based on a large, representative sample and enjoys high response rates.
- MECS obtains accurate information on the total amount of electricity used at the site level. This effectively prevents wild overestimates of motor system energy and provides an intuitive check on the reasonableness of the end-use allocations.
- The MECS sample is sufficiently large to provide reasonably precise estimates of energy use for important four-digit SIC groups. This is particularly important in such industries as Chemicals (SIC 28) and Primary Metals (SIC 33). For example, Industrial Inorganic Chemical Plants (SIC 2819) and Industrial Gas Producers (SIC 2813) each use more motor system energy than many two-digit industrial groups. However, their patterns of electricity and motor system energy use are quite different.

Limitations of the MECS estimates.
While the MECS results serve as an excellent point of departure for detailed analyses of the motor system population and energy use, they have the following limitations.

- Given that the electric end-use allocations are not corroborated by other kinds of observations, their accuracy can be questioned. This is particularly the case for industries dominated by large facilities that use huge amounts of electricity: Pulp and Paper, Primary Metals, certain chemical subindustries.
- MECS does not provide any detail of the distribution of the motor system population by size, application, operating hours, part load, or other characteristics that can be used to assess energy savings opportunities.

THE MARKET ASSESSMENT INVENTORY: COMPARISON TO MECS

Comparison of motor system energy estimates.
The primary purpose of MECS is to estimate total energy use by energy source for all subdivisions of manufacturing. Secondarily it produces an estimate of electric use in motor systems, among other end uses. The primary purpose of the MAI was to characterize the population of manufacturing motor systems in great detail. As a byproduct, we produced estimates of motor energy use for all but the two smallest two-digit manufacturing groups, and for the manufacturing sector as a whole.

[5] There is likely to be some motor system energy in other categories including “Process Heating” and “Other”. The survey form provides the following end uses as examples of end uses to be included under “Process Heating”: kilns, furnaces, ovens. This suggests that most respondents would generally think of uses in which electricity is used directly to produce heat, rather than to drive ancillary equipment, such as induced draft fans or boiler water pumps, which could also be covered under machine drive.

[6] Communication with Dwight French, Director of the Energy Consumption Division of EIA.

Although the scale, time period covered, and basic methodological approach of the two surveys are different, it is nonetheless important to compare the motor system energy estimates they developed. If the MAI's estimates of motor system energy at the two-digit SIC level differed greatly from that of MECS, then we would suspect that there was something wrong with the sampling plan or data collection protocol. As Table 1-6 shows, the motor system energy estimates generated by the two surveys are generally very close, within 6 percent for the manufacturing sector as a whole. We would expect the MAI estimates to be somewhat higher than the MECS estimates for a number of reasons.

- According to Energy Information Administration statistics on industrial electric consumption and updates of the Annual Census of Manufacturers, electric use in the manufacturing sector increased from 1994 to 1996 by approximately 1.4 percent.
- The MAI is likely to pick up some equipment whose electric consumption is classified under other categories in the MECS.

Table 1-6: Comparison of MAI and MECS 1994 Estimates of Motor System Energy by Two-Digit SIC Group

SIC	Industry Description	Motor Energy (GWh/Year) MECS 94	MAI	Survey Estimate as % of MECS Estimate
20	Food and Kindred Products	47,374	37,797	80%
21	Tobacco Products	909	–	–
22	Textile Mill Products	20,890	16,750	80%
23	Apparel and Other Textile Products	3,108	1,168	38%
24	Lumber and Wood Products	15,589	22,946	147%
25	Furniture and Fixtures	3,662	3,694	101%
26	Paper and Allied Products	99,350	99,594	100%
27	Printing and Publishing	8,570	5,961	70%
28	Chemicals and Allied Products	135,518	144,362	107%
29	Petroleum and Coal Products	42,658	51,938	122%
30	Rubber and Miscellaneous Plastics Products	25,914	36,610	141%
31	Leather and Leather Products	510	491	96%
32	Stone, Clay, and Glass Products	22,305	2,231	10%
33	Primary Metal Industries	46,093	87,935	191%
34	Fabricated Metal Products	17,706	7,296	41%
35	Industrial Machinery and Equipment	15,034	7,378	49%
36	Electronic and Other Electric Equipment	11,605	13,243	114%
37	Transportation Equipment	17,291	29,549	171%
38	Instruments and Related Products	4,780	6,487	136%
39	Miscellaneous Manufacturing Industries	2,337	-	-
		541,203	***575,428***	***106%***

At the two-digit SIC level, the divergence between the MAI and MECS results is more pronounced. This is to be expected given the relatively small size of the MAI samples at the two-digit level. Among the five of six major process industries which use huge amounts of motor system energy (Food, Textiles, Paper, Chemicals, Petroleum, and Primary Metals), the difference between the MAI and the MECS energy estimates was 22 percent or less. The one exception was in Primary Metals where the MAI estimate was 91 percent higher than the MECS estimate. A number of factors may have influenced this result. First, as discussed above, Primary Metals facilities use large amounts of electricity in a variety of processes, including motor systems and process heat. Small but consistent misallocations of energy among these end uses by participants in the MECS could lead that survey to underestimate motor system electricity. The 1994 MECS estimates SIC 33 motor system energy at 30 percent of total electricity (purchased and net on-site generation). The MAI estimate would come in at 57 percent of total electricity. Second, as in most large industries, there is a great deal of variation in the nature and intensity of motor energy use within subdivisions. With only 23 sites in the sample, it was difficult to account for all of this variation, and the kinds of factories that fell into the sample may have had unusually high proportions of motor system energy consumption. Similarly, the low level of motor system energy use found in SIC 32 may have been due to the small sample (six sites) and the nature of the processes at those sites.

Use of MECS versus MAI estimates.
Throughout this report, we will be making reference to the 1994 MECS estimates of motor system energy use and using various indicators of energy intensity and cost based on those estimates. We have attempted to be as consistent as possible in our choice between MECS motor system estimates and the estimates generated by the MAI. Table 1-7 displays uses to which the different estimates are put, as well as our criteria for each decision.

Table 1-7: Application of MECS and MAI Results

Application	Rationale
MAI Applications	
• Detailed distributions of motor system population and energy use by HP, application, and other attributes.	• Only the MAI collects information on motor attributes. • Each motor system observation contains sufficient information to estimate its annual energy consumption.
• Estimates of motor system energy savings.	• The methods used to estimate energy savings directly incorporate observations on individual motor systems, including the efficiency of the motor, the application of the motor system, and detailed attributes of the system including control mechanisms, hours of use, motor size, and type.
MECS Applications	
• Estimates of motor system energy use at the four-digit SIC level.	• The MAI sample was designed to yield representative results only at the two-digit SIC level for manufacturing industries.
• Development of indices of motor system energy intensity and costs, e.g., motor system energy per employee or motor system energy costs as a percentage of operating costs for various industries.	• Estimates of the component statistics for these indices generally come from Census surveys which make use of the same sampling frame and procedures, that is, the Census of Manufactures and the Annual Survey of Manufactures.

PRECISION OF MAI ESTIMATES

Most of the description of the motor system population and energy savings opportunities contained in this report proceeds from estimates of motor system energy used by various groups of motor systems in the population. We estimated 90-percent confidence intervals for our estimates of total motor system energy in all manufacturing, total motor system energy in each two-digit manufacturing SIC group, and each major application (pumps, fans, air compressors, and other machines).

Table 1-8 shows the 90-percent confidence interval for the MAI estimate of motor system energy for the relevant two-digit SIC group and for manufacturing as a whole.[7] The 90-percent confidence interval for total manufacturing motor system energy was ± 18 percent. The confidence intervals for total motor system energy in the individual two-digit SIC groups ranged from ± 4 percent in Stone, Clay, and Glass (SIC 32) to ± 81 percent in Primary Metals (SIC 33). The broadest confidence intervals are for Primary Metals, SIC 33 (± 81 percent) and Chemicals

[7] The 90-percent confidence interval can be interpreted as follows: There is a 90-percent probability that the actual total motor system energy consumption is within “X” percent of the estimate based on sample observations.

SIC 28 (± 46 percent). The high variance in these groups reflects the extreme diversity of motor usage in the chemical and steel industries. For example, motor system energy use per employee in Industrial Gases (SIC 2811) is over 3 million kWh per year, versus 270,000 kWh per year in Plastic Materials and Resins (SIC 2821).

Given the relatively small size of the MAI sample, the precision of these estimates is high. However, the further the results of the inventory are disaggregated, the less precise the estimates of population attributes become. Readers should keep this in mind in interpreting the inventory results presented below.

Table 1-8: Precision of Motor System Energy Estimates by Two-Digit SIC Group

SIC	Industry Description	MAI Estimate of Motor System Energy Use (GWh/Year)	90% Confidence Interval
20	Food and Kindred Products	37,797	±16%
21	Tobacco Products	–	–
22	Textile Mill Products	16,750	±22%
23	Apparel and Other Textile Products	1,168	±10%
24	Lumber and Wood Products	22,946	±27%
25	Furniture and Fixtures	3,694	±18%
26	Paper and Allied Products	99,594	±28%
27	Printing and Publishing	5,961	±22%
28	Chemicals and Allied Products	144,362	±46%
29	Petroleum and Coal Products	51,938	±13%
30	Rubber and Miscellaneous Plastics Products	36,610	±10%
31	Leather and Leather Products	491	
32	Stone, Clay, and Glass Products	2,231	±4%
33	Primary Metal Industries	87,935	±81%
34	Fabricated Metal Products	7,296	±16%
35	Industrial Machinery and Equipment	7,378	±14%
36	Electronic and Other Electric Equipment	13,243	±9%
37	Transportation Equipment	29,549	±38%
38	Instruments and Related Products	6,487	±12%
39	Miscellaneous Manufacturing Industries	-	-
	Total Manufacturing	***575,428***	***±18%***

OVERVIEW OF MOTOR SYSTEM ENERGY USE IN INDUSTRY

In this section, we provide a general overview of the scale of motor energy consumption and costs in industry.

SCALE OF MOTOR SYSTEM ENERGY USE

According to the results of the MAI, there are roughly 12.4 million electric motors of more than 1 horsepower in service in U.S. manufacturing plants. Based on a combination of survey results, previous government surveys, and secondary literature, we estimate that there are an additional 2.5 million integral horsepower motors in use in the non-manufacturing industries covered by this study. Table 1-9 shows the distribution of motor system energy between manufacturing and non-manufacturing industries, and among major subdivisions within those categories.

Table 1-9: Motor System Energy Use by Major Industry Group, 1994

Industry Categories	Net Electric Demand* (GWh/Year)	Motor System Energy (GWh/Year)	Motor System Energy as % of Total Electricity
Manufacturing	**917,834**	**541,203**	**59%**
Process Industries (SICs 20,21,22,24,26,27,28,29,30,31,32)	590,956	419,587	71%
Metal Production (SIC 33)	152,740	46,093	30%
Non-metals Fabrication (SICs 23,25,36,38,39)	106,107	50,031	47%
Metals Fabrication (SICs 34,35,37)	68,031	25,492	37%
Non-manufacturing	**167,563**	**137,902**	**82%**
Agricultural Production (SICs 01, 02)	32,970	13,452	41%
Mining (SICs 10, 12,14)	44,027	39,932	90%
Oil and Gas Extraction (SIC 13)	33,038	29,866	90%
Water Supply, Sewage, Irrigation (SICs 494, 4952,4971)	57,528	54,652	95%
Total All Industrial	***1,085,397***	***679,105***	***62.6%***

* Net electric demand is the total of purchased kWh plus kWh generated on site less kWh sold to off-site users.
Sources: MECS 1994, Department of Agriculture 1992, Census of Mineral Industries 1992, Burton Environmental et al. 1993.

Industrial motor system energy in the context of national electric usage.
In 1994, motors systems used for production processes only (not including facility heating and ventilating) consumed 679 billion kWh, or 23 percent of all electricity sold in the United States that year (2,931 billion kWh). If the energy associated with industrial HVAC systems is added, this total comes to 747 billion kWh, or 25 percent of all electric sales.

Motor system energy use in the context of industrial energy usage.
Process motor system energy accounts for 63 percent of all electricity used in industry; 59 percent of all electricity used in manufacturing. Motor system energy accounts for 8.5 percent of all manufacturing energy consumption from all sources, or 22 percent, if losses in the conversion of thermal to electrical energy and transmission are taken into account.

Concentration of motor system energy by industry.
Motor system energy usage is highly concentrated by industry. Table 1-10 shows that the top 10 two-digit industries (after consolidating mining into one group) account for 75 percent of all motor system energy use in industry.

Table 1-10: Motor System Energy Use by Top 10 Two-Digit Industrial Groups

SIC	Industry Group	Motor Systems Energy (GWh/Year)	Percent of Total Industrial Motor System Energy
28	Chemicals and Allied Products	135,518	20%
26	Paper and Allied Products	99,350	15%
20	Food and Kindred Products	47,374	7%
33	Primary Metal Industries	46,093	7%
29	Petroleum and Coal Products	42,658	6%
10,12,14	Mining	39,932	6%
494	Water Supply	26,885	4%
13	Oil and Gas Extraction	26,836	4%
30	Rubber and Misc. Plastics	25,914	4%
22	Textile Mill Products	20,890	3%
	Subtotal	***511,450***	***75%***
	Total (All Industrial)	679,105	

Concentration of motor system energy use in manufacturing.

The concentration of motor system energy in manufacturing is even more pronounced than it is in industry as a whole. Table 1-11 shows the 10 four-digit SIC groups with the highest estimated motor system energy use. These 10 SIC groups account for nearly half of all manufacturing motor system energy use (and a commensurate share of potential savings). These groups include only 3,583 facilities, or 1.5 percent of all manufacturing plants. The largest 780 plants in these groups account for over one-third of all manufacturing motor energy use. These plants are owned by roughly 500 separate companies.

Table 1-11: Concentration of Motor Energy Use in Manufacturing

SIC	Industry Categories	Motor System Energy Use (mm kWh/Yr)	% of Total Manufacturing Motor System Energy
2621	Paper Mills	55,777	10.3%
2911	Petroleum Refining	40,805	7.5%
2819	Industrial Inorganic Chemicals, nec.	37,232	6.9%
2631	Paperboard Mills	27,007	5.0%
3312	Blast Furnaces and Steel Mills	25,323	4.7%
2869	Industrial Organic Chemicals, nec.	28,721	5.3%
2813	Industrial Gases	21,733	4.0%
2821	Plastics Materials and Resins	13,667	2.5%
3241	Cement, Hydraulic	9,147	1.7%
2611	Pulp Mills	6,402	1.2%
	Total of Top 10	***265,814***	***49.1%***
	Total: All Manufacturing	***541,203***	

Sources: MECS 1994, Census of Manufactures 1992.

Motor system energy costs in the context of total operating costs.

In 1994, manufacturing facilities spent $23.4 billion for motor system energy. The non-manufacturing industries covered in this study spent an additional $6.6 billion. Despite these large numbers, motor system energy costs constituted only 0.7 percent of total operating costs for all manufacturing industries. At the two-digit level, motor system energy costs amounted to more than 1 percent of total energy costs for six groups: Paper; Chemicals; Textiles; Lumber and Wood Products; Stone, Clay and Glass Products; and Primary Metals. Only in Paper and Allied Products did motor system energy costs exceed 2 percent of operating costs. The low ratio of motor system energy costs to total operating costs may help explain the scant attention motor system efficiency has received from most industrial establishments.

Don Meadows, TAPPI Journal

Paper mills like this one could save an average of $659,000 a year through motor system efficiency.

As with energy, motor system costs are highly concentrated in a small number of industries. Table 1-12 displays motor system energy use and potential savings per establishment in the 10 four-digit SIC groups with the highest annual motor energy consumption. In all these industries, the annual cost of motor system energy in a typical plant exceeds $1 million; in steel mills it is $6 million. Potential savings at the typical plant are also very large, ranging from $90,000 per year in the Industrial Organic Chemicals sector to nearly $1 million per year in petroleum refineries.

Table 1-12: Financial Impact of Motor Energy Consumption and Savings: Selected Industries

Industry Groups	Motor System Costs/Estab.	Motor Energy Costs/Total Operating Costs	Savings per Estab. per Yr.	Savings as % of Operating Margin
Paper Mills	$4.6 mm	6.5%	$659,000	5%
Petroleum Refining	$5.6 mm	1.4%	$946,000	1%
Industrial Inorganic Chemicals, nec.	$1.6 mm	10.4%	$283,000	6%
Paperboard Mills	$3.0 mm	6.4%	$492,000	5%
Blast Furnaces and Steel Mills	$6.0 mm	2.1%	$358,000	2%
Industrial Organic Chemicals, nec.	$1.3 mm	1.0%	$91,000	1%
Industrial Gases	$1.1 mm	21.7%	$116,000	13%
Plastics Materials and Resins	$1.5 mm	1.5%	$121,000	1%
Cement, Hydraulic	$2.2 mm	9.6%	$219,000	4%
Pulp Mills	$1.7 mm	6.7%	$483,000	5%

Sources: MECS 1994, Bureau of Economic Analysis 1997, Census of Manufactures 1993, Savings Analysis in Section 2.

DETAILED INVENTORY FINDINGS: MANUFACTURING INDUSTRIES

In this section we present detailed findings on the manufacturing motor systems inventory, concentrating on the distribution of motors and motor system energy by the following characteristics:

- Motor size: Horsepower or kW;
- Application and process;
- Hours of operation;
- Part load;
- Efficiency; and,
- Saturation of adjustable speed drives.

The presentation in this section focuses at the national level. In most cases, we disaggregate our findings by SIC group for the five largest motor system using SIC categories. These account for 36 percent of the motors and 73 percent of the motor system energy in manufacturing. Appendix B contains complete detailed tables of inventory characteristics for all two-digit manufacturing groups except Tobacco Products and Miscellaneous.

Estimation of motor system energy.
We estimated the annual energy use of every motor system inventoried for this project. The energy estimate was based on the standard engineering formula.

$$\textit{Annual Energy} = \frac{\textit{horsepower} \times 0.746 \times \textit{operating hours} \times \textit{motor loading}}{\textit{efficiency}}$$

The value of the parameters in the energy equation for each motor system was established as follows:

- Horsepower: Nameplate horsepower observed or information from escort.
- Constant to convert HP to kW: 0.746.
- Hours of operation: Reported hours of operation for the department in which the motor system is located multiplied by the diversity factor for the individual motor system provided by the escort or machine operator.
- Part load: Average measured part load for the application category of the sampled motor system: pump, fan, air compressor, or other.[8] These figures were developed from instantaneous load measurements taken as part of the inventory.
- Nominal efficiency: Nameplate efficiency observed. If no efficiency was observed on the nameplate, the MotorMaster+ default efficiency for the horsepower class was used.[9]

DISTRIBUTION BY HORSEPOWER SIZE

Motor systems in the 1–5 horsepower range account for 59 percent of the motors in the entire manufacturing inventory. However, they account for only 5 percent of the energy use. Motors over 200 horsepower account for only one percent of the inventory, but use 45 percent of the energy. Table 1-13 shows the distribution of the motor population by horsepower class for selected SIC groups and for manufacturing as a whole. Table 1-14 shows the distribution of motor energy by the same categories.

Table 1-13: Distribution of Motor Population by Horsepower Size: Manufacturing Number of Units in Service

Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	*All SICs Percent*	*All SICs Number*
1–5	42.4%	52.2%	55.0%	32.0%	65.8%	63.9%	***58.8%***	***7,306,080***
6–20	30.0%	22.3%	26.1%	38.6%	22.6%	25.6%	***26.4%***	***3,288,035***
21–50	14.5%	13.0%	10.7%	18.9%	6.2%	7.2%	***9.1%***	***1,129,527***
51–100	5.9%	6.3%	3.5%	6.2%	2.4%	1.9%	***2.9%***	***363,940***
101–200	4.1%	3.1%	2.1%	2.8%	1.8%	1.2%	***1.8%***	***220,908***
201–500	2.2%	2.0%	1.7%	1.0%	0.9%	0.2%	***0.7%***	***86,836***
501–1000	0.6%	0.9%	0.7%	0.3%	0.4%	0.0%	***0.2%***	***28,047***
1000+	0.4%	0.3%	0.3%	0.2%	0.0%	0.0%	***0.1%***	***10,958***
All Sizes	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	***100.0%***	***12,434,330***

Table 1-14: Distribution of Motor System Energy by Horsepower Size: Manufacturing

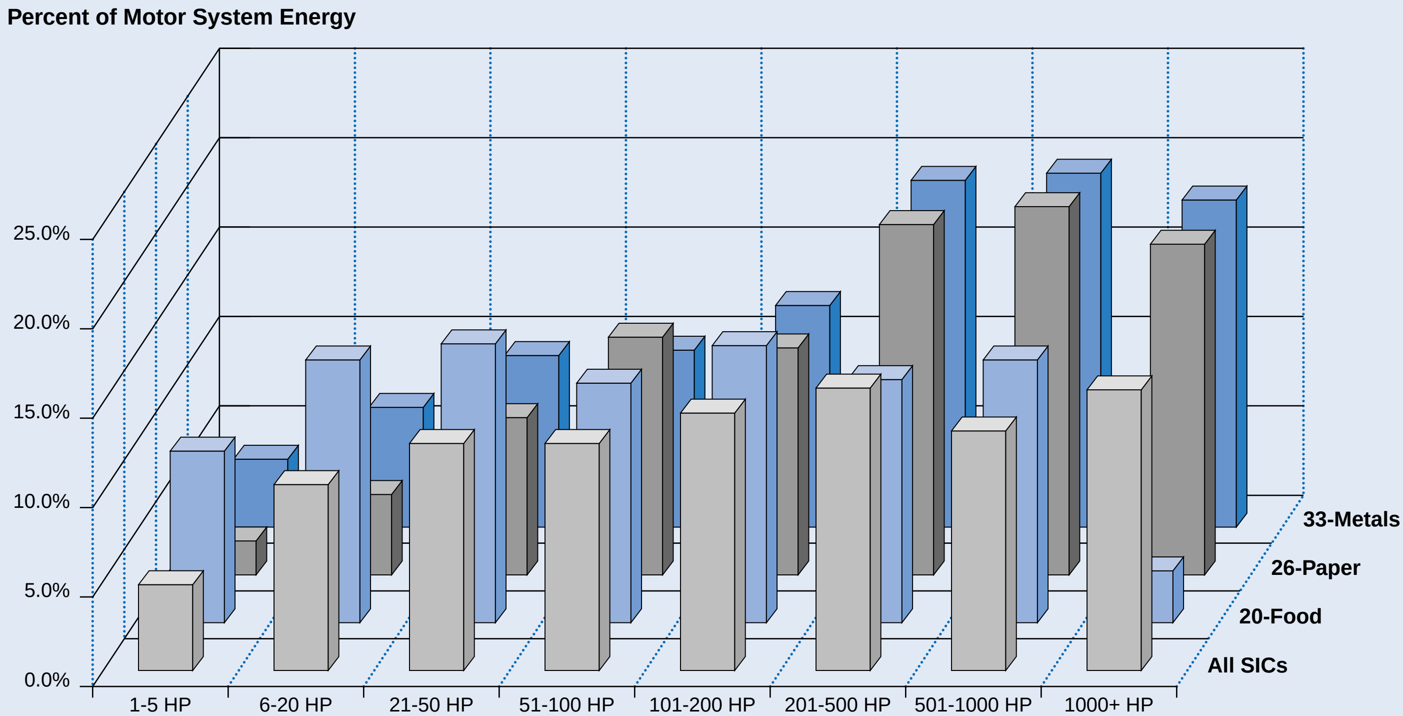
Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	*All SICs Percent*	*All SICs Number*
1–5	1.6%	1.9%	3.8%	1.0%	9.6%	10.4%	***4.8%***	***27,807***
6–20	6.4%	4.5%	6.7%	5.9%	14.7%	20.7%	***10.4%***	***60,122***
21–50	9.1%	8.8%	9.6%	12.4%	15.6%	19.8%	***12.7%***	***73,111***
51–100	9.3%	13.3%	9.9%	12.2%	13.4%	17.0%	***12.7%***	***72,924***
101–200	14.3%	12.7%	12.4%	13.9%	15.5%	16.9%	***14.4%***	***83,099***
201–500	18.1%	19.6%	19.4%	16.1%	13.6%	9.4%	***15.8%***	***90,819***
501–1000	13.7%	20.6%	19.8%	11.0%	14.7%	5.3%	***13.4%***	***77,238***
1000+	27.5%	18.5%	18.3%	27.4%	2.9%	0.5%	***15.7%***	***90,307***
All Sizes	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	***100.0%***	***575,428***

8 Part load is defined as the ratio of the instantaneous output from a piece of equipment to the equipment's rated load. Most motors, pumps, fans, and air compressors operate most efficiently at part loads that are within 15 to 20 percent of their rated loads.

9 MotorMaster+ is a software program developed by Washington State University that supports electric motor selection decisions. It contains a current database of electric motors offered by most major manufacturers, as well as a set of default assumptions concerning the nominal efficiency of motors currently in use. These assumptions are reviewed and revised periodically by experts in the field.

Figure 1-2 illustrates the differences between industries in distribution of motor system energy by horsepower class. In manufacturing as a whole, the distribution of motor system energy across horsepower classes above the 1–5 range is fairly even. In Paper and Primary Metals, which have high levels of motor system energy use per establishment (9 GWh/Year and 18 GWh/Year, respectively), the distribution of motor system energy is concentrated in the higher horsepower ranges, especially in Metals. These large motors are generally driving very large machines or fluid systems that provide heat or compressed air to the entire facility. Food Processing, on the other hand, has a relatively low level of motor energy use per establishment (3 GWh/Year). Its motor energy use is concentrated in the 1–20 and 51–100 horsepower ranges. Many of these are systems that provide service to the entire facility. However, food processing plants are generally smaller than paper or metals facilities.

Figure 1-2: Distribution of Motor Energy by Horsepower—All Manufacturing and Selected SIC Groups



HOURS OF OPERATION

The high concentration of motor system energy in the larger horsepower ranges can be explained to some extent by the distribution of motor systems by hours of operation. As Table 1-15 shows, annual hours of operation increase fairly consistently with motor size, particularly in the process industries. This reflects the use of large motors to provide facility-level services such as compressed air or pumping of finished products. In Paper and Chemicals for example, motors systems in the 1000+ horsepower range were reported to operate more or less continuously. (There are 8,760 hours in a year.) On average, motor systems in the 501–1000 horsepower range were reported to be operating 80 percent of the time.

Table 1-15: Annual Motor System Operating Hours by Horsepower Size: Manufacturing

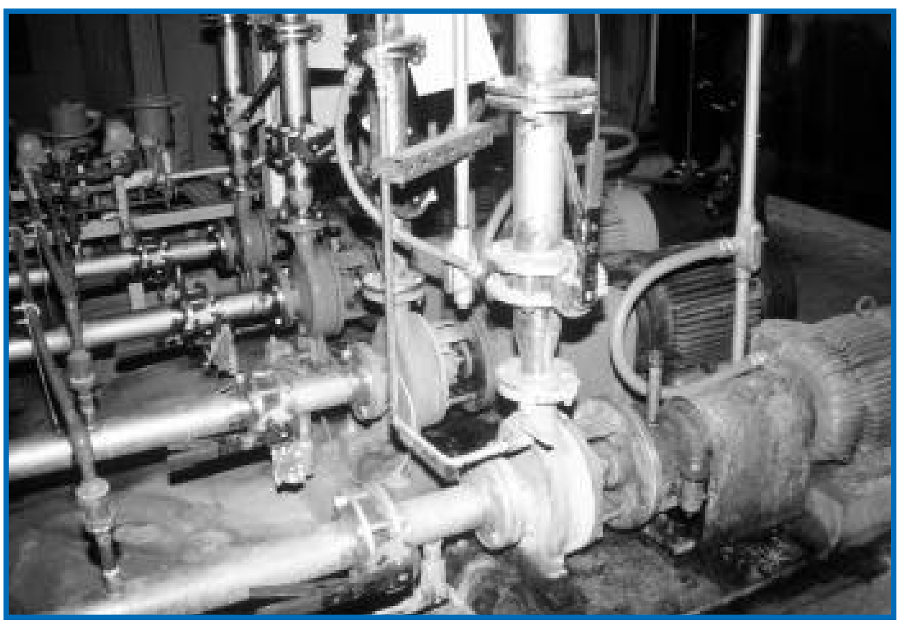
Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	All SICs Number
1–5	4,082	3,997	4,377	1,582	3,829	2,283	2,745
6–20	4,910	4,634	4,140	1,944	3,949	3,043	3,391
21–50	4,873	5,481	4,854	3,025	4,927	3,530	4,067
51–100	5,853	6,741	6,698	3,763	5,524	4,732	5,329
101–200	5,868	6,669	7,362	4,170	5,055	4,174	5,200
201–500	6,474	6,975	7,114	5,611	3,711	5,396	6,132
501–1000	7,495	7,255	7,750	5,934	5,260	8,157	7,186
1000+	7,693	8,294	7,198	6,859	6,240	2,601	7,436
All Sizes	6,333	6,748	6,465	4,332	4,584	3,678	5,083

DISTRIBUTION BY APPLICATION

Previous studies have identified the major fluid systems—pumps, fans, and compressors of various types—as the applications that account for the greatest portion of motor system energy. One frequently cited study based on various marketing research sources estimated that 49 percent of total manufacturing motor system energy was used by pumps, fans, and compressors. (RDC 1991) The results of the MAI place this figure at 61 percent. The heavy concentration of motor system energy in fluid systems is an important finding because methods to improve the efficiency of such systems are fairly well understood *and* because virtually every industry uses these systems. They are particularly heavily concentrated in the process industries.

Tables 1-16 and 1-17 show the distribution of the motor population and motor system energy use by application for selected SIC groups. As we previously saw in the motor size distributions, the differences between industries is pronounced. Pumps account for 59 percent of total motor system energy in the petroleum industry, versus 25 percent for all manufacturing. In Primary Metals, 47 percent of motor system energy is consumed by material handling equipment versus 12 percent in manufacturing as a whole. Compressed air systems account for 28 percent of motor system energy in Chemicals, versus 16 percent in all manufacturing facilities. Figure 1-3 illustrates these differences.

Pumps account for 25% of total motor system energy in all manufacturing. The Heileman Division of Stroh Brewery Company showed how a pump optimization project at its Lacrosse facility cut the cooling system's energy use by half.



Energy Center of Wisconsin

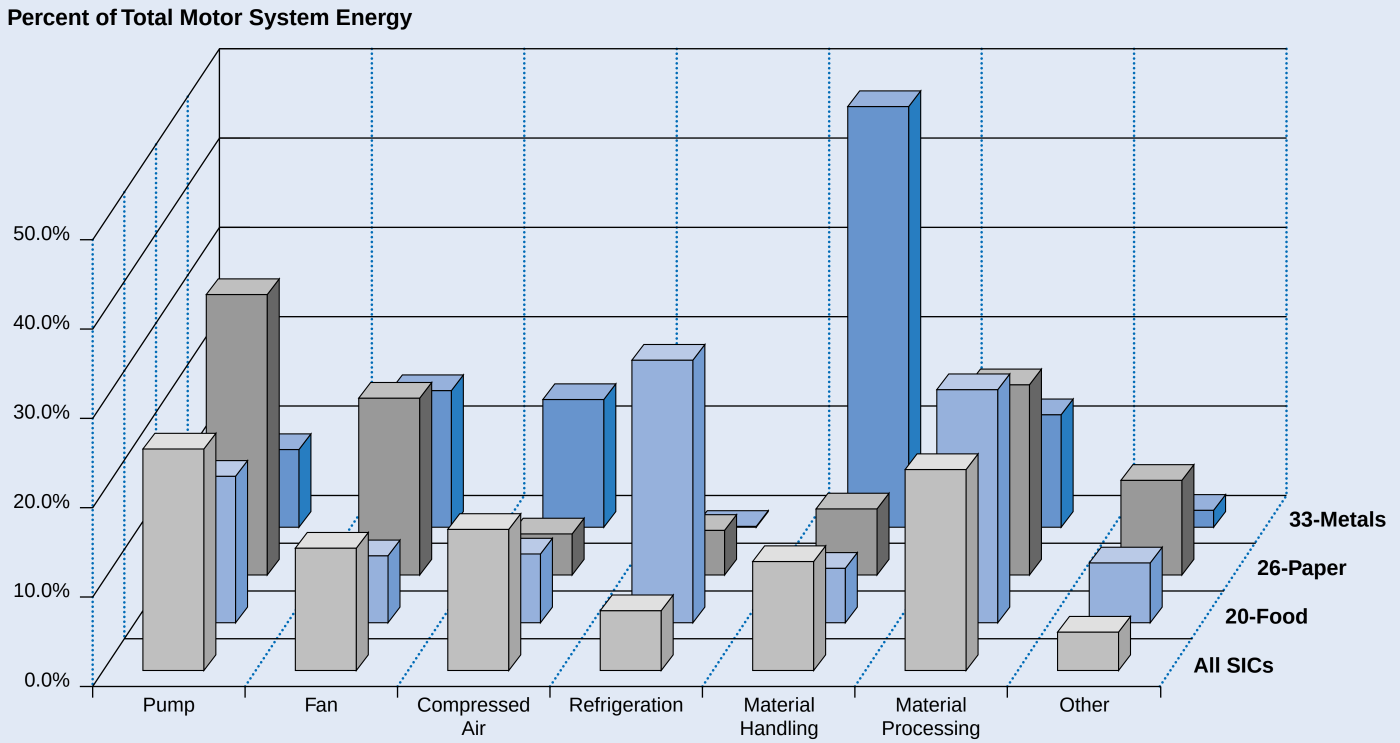
Table 1-16: Distribution of Motor Population by Application

Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	*All SICs Percent*
Pump	42.2%	22.3%	17.9%	43.3%	22.7%	13.9%	***19.7%***
Fan	10.4%	13.4%	14.1%	10.7%	12.9%	10.6%	***11.2%***
Compressed Air	4.1%	3.3%	6.0%	3.2%	3.8%	5.6%	***5.1%***
Refrigeration	1.8%	0.4%	0.3%	0.6%	2.1%	0.6%	**0.8%**
Subtotal: Fluid Systems	58.5%	39.4%	38.4%	57.8%	41.5%	30.7%	***36.8%***
Material Handling	5.1%	24.6%	34.9%	12.4%	23.9%	15.0%	***16.8%***
Material Process	33.7%	29.3%	20.3%	28.1%	31.1%	50.0%	***42.2%***
Other	2.6%	6.8%	6.4%	1.8%	3.4%	4.3%	***4.2%***
Subtotal: Other Systems	41.5%	60.6%	61.6%	42.2%	58.5%	69.3%	***63.2%***
All Applications	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	***100.0%***

Table 1-17: Distribution of Motor System Energy Use by Application

Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	*All SICs Percent*
Pump	26.0%	31.4%	8.7%	59.0%	16.4%	19.0%	***24.8%***
Fan	11.9%	19.8%	15.3%	9.5%	7.5%	13.5%	***13.7%***
Compressed Air	27.7%	4.6%	14.3%	15.3%	7.7%	15.0%	***15.8%***
Refrigeration	7.7%	5.0%	0.1%	0.7%	29.4%	7.1%	***6.7%***
Subtotal: Fluid Systems	73.3%	60.7%	38.4%	84.4%	61.1%	54.6%	***61.0%***
Material Handling	1.4%	7.4%	47.1%	2.6%	6.1%	10.3%	***12.2%***
Material Process	23.6%	21.3%	12.6%	11.1%	26.1%	31.0%	***22.5%***
Other	1.8%	10.6%	1.9%	1.9%	6.7%	4.1%	***4.3%***
Subtotal: Other Systems	26.7%	39.3%	61.6%	15.6%	38.9%	45.4%	***39.0%***
All Applications	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	***100.0%***

Figure 1-3: Distribution of Motor Energy by Application—All Manufacturing and Selected SIC Groups

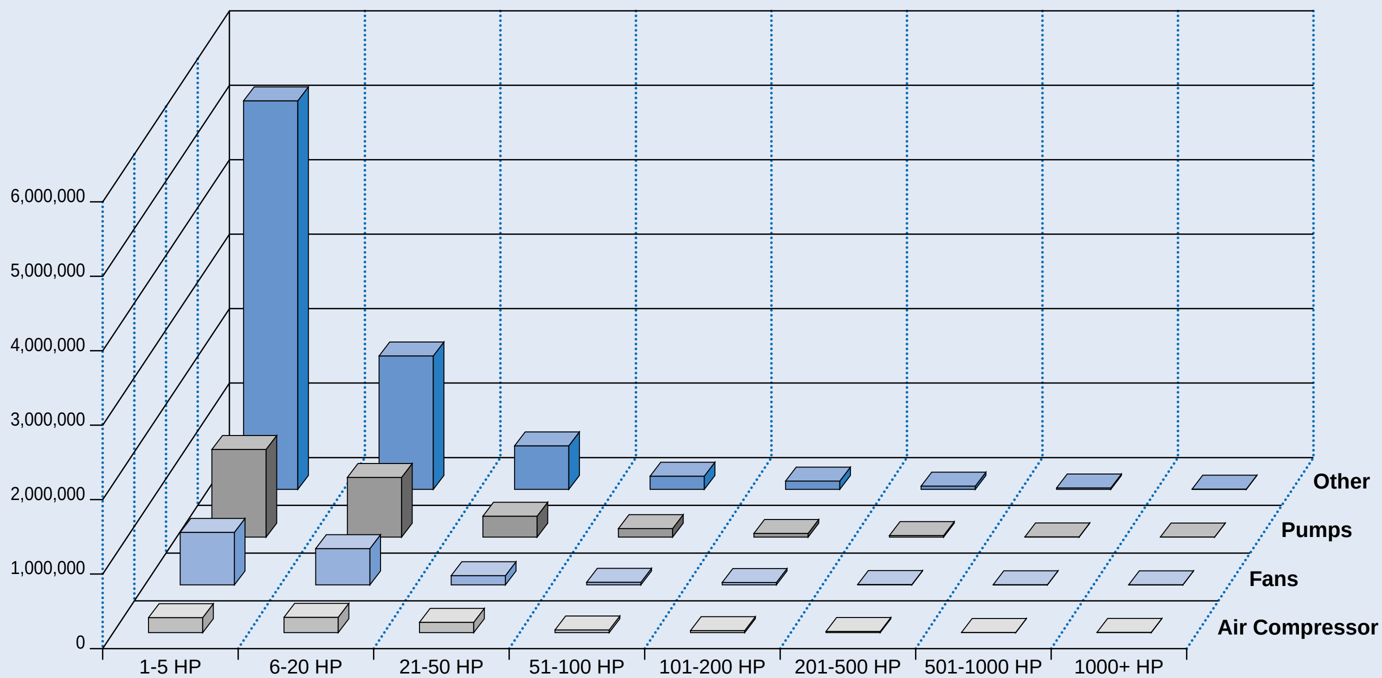


DISTRIBUTION OF MOTOR SYSTEM POPULATION AND ENERGY BY SIZE AND APPLICATION

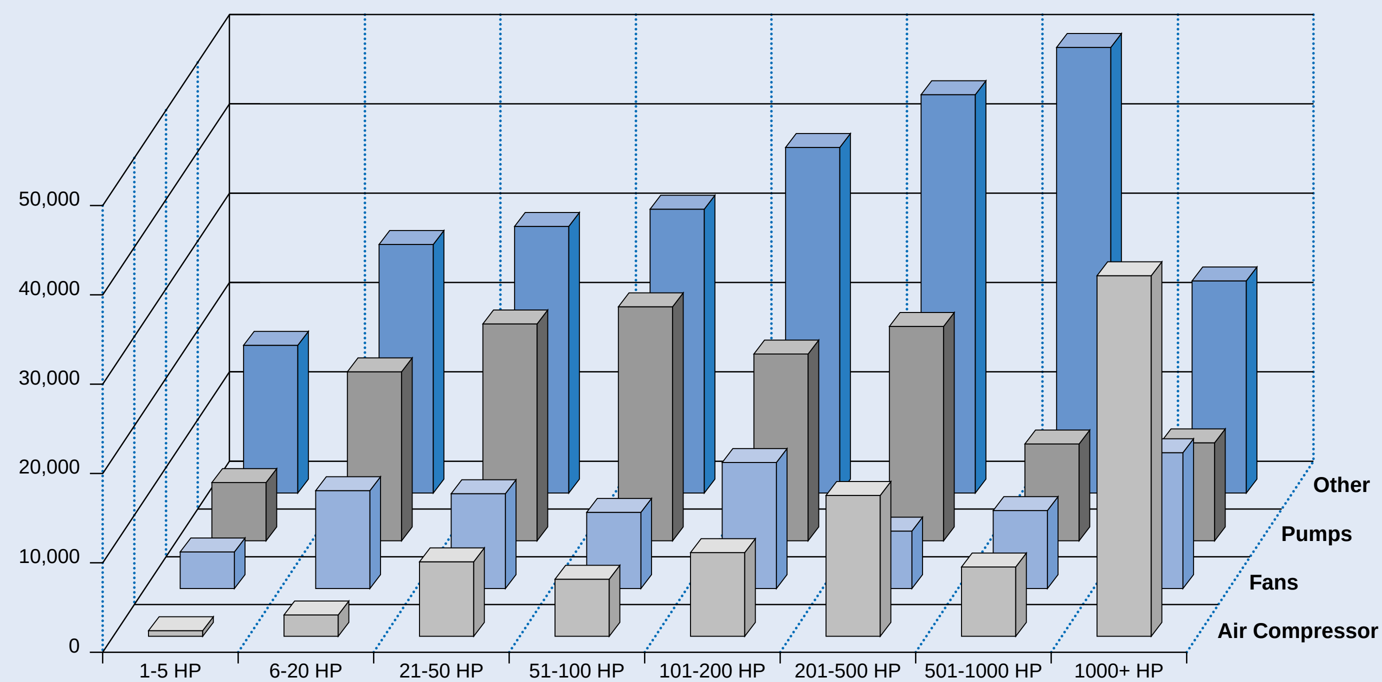
The overall layout of the motor population in terms of units and energy, as well as the differences between industries become clearer when motor system energy is disaggregated by motor size *and* application. Figure 1-4 shows the distribution of motors and motor system energy by size and application. The striking aspect of this chart is the extreme concentration of the motor population in relatively small, non-fluid applications.

Figure 1-4: Distribution of Motor Population and Energy Use by Horsepower Class and Application

Motor Population (Number of motors)



Motor System Energy Consumption (GWh/Year)



Motor system energy is considerably more evenly distributed among size and application categories than the population. As discussed above, total motor system energy is fairly evenly distributed among the horsepower size categories from 6 to 20 HP and above. At the application level, motor system energy for non-fluid systems is distributed fairly evenly by horsepower, and accounts for about 40 percent of all motor system energy use. Among the fluid system categories, compressed air system energy is concentrated in the highest motor HP range—1,000 horsepower and above. Pumping system energy, by contrast, is spread fairly evenly among the HP categories from 6 to 200 HP.

DISTRIBUTION OF MOTOR SYSTEMS AND ENERGY BY PART LOAD

It is widely observed by persons familiar with industrial motor systems operation that a significant portion of motors operate for extended periods below the efficient range of part loads. Below 40 percent part load, the efficiency of motors drops off precipitously. If a motor system runs consistently below 40 percent, considerable energy savings can be achieved by reducing the size of the motor. (E-Source 1993) Prior to the MAI, several studies had been undertaken to assess the extent of motor oversizing. All of these use instantaneous load measurements on small, unrepresentative samples of motors. (Gordon et al. 1994, Kotiuga et al. 1995) Such evidence as these studies provide suggests that a large portion of industrial motors—perhaps 20–40 percent generally operate at low part loads.

The inventory database contains instantaneous load measurements for 1,991 motors. These measurements were taken at 221 of the inventoried sites. While we attempted to take measurements at all of the sites, this was not possible in all cases. At some factories, processes were shut down for maintenance or retooling; at others the electrician was not available to connect the meters.

The field engineers selected motors for measurement from the completed inventory list using random methods. The selection method was structured so that the probability of selection increased with motor size (a proxy for motor system energy use). Prior to taking load measurements, the field engineers consulted with the escort to verify that the motor was operating under load and in “typical conditions.”

The distribution of the load measurements are shown in Tables 1-18 and 1-19. These distributions are properly weighted to reflect the representation in the population of the sample facilities and the sample motor systems within those facilities. Of the 1,991 motors measured, 44 percent were loaded at less than 40 percent. Table 1-18 displays the loading by motor application and shows that the proportion of motors under loaded (less than 40% of full load) does vary by the motor application. Of the three fluid applications analyzed, air compressors are most consistently fully loaded with only 15 percent underloaded. Thirty percent of the fan systems measured and 39 percent of the pump systems measured were underloaded. “Other” motor systems—those that generally did not involve a fluid process—had the highest proportion of underloaded motors: 55 percent.

When pump and fan systems are significantly underloaded, it is likely that the system as a whole is operating far from its best (i.e. most efficient) operating point.[10] The high percentage of underloaded motors in pump and fan systems suggest that significant savings are available in these systems through adjustments to the system and downsizing of the drive motors.

The Motor System and Practices Inventory did not collect data which might shed light on the reasons for the pronounced differences between applications in percentage of underloaded motors. A number of studies note that conventional engineering practice has supported

10 The operating point is defined by the combination of static pressure, flow, and input power at which the pump is operating. The further actual operating conditions depart from the design point or best efficiency point, the lower the operating efficiency of the pump.

oversizing of pumps to accommodate potential large fluctuations in flow, thereby avoiding overflows and the damage they can cause. (Easton Consultants 1996, BPA 1992) However, we are not aware of sizing conventions that would lead to the large difference between fan and compressed air systems in the percentage of underloaded motors. Also, the higher loading of air compressors does not necessarily indicate greater system efficiency. Some of the load may consist of leaks and bypasses which do no productive work. Finally, the very high percentage of underloaded motors driving "other" machines is striking. It may reflect the diversity of the work these machines do and the lack of widely applicable sizing conventions.

Table 1-18: Distribution of Motors by Part Load and Application

Part Load (Percentage of Full Load)	Application				
	Air Compressor	Fan	Other	Pump	All
< 40%	15%	30%	55%	39%	44%
40 to 120%	84%	69%	43%	56%	53%
> 120%	1%	1%	2%	4%	2%

As Table 1-19 shows, the distribution of part loads does not vary significantly or consistently with the size of the motor.

Table 1-19: Loading by Horsepower

Part Load (Percentage of Full Load)	Horsepower Category					
	1 to 5 HP	6 to 20 HP	21 to 50 HP	51 to 100 HP	101 to 200 HP	200+ HP
< 40%	42%	48%	39%	45%	24%	40%
40 to 120%	54%	51%	60%	54%	75%	58%
> 120%	4%	1%	1%	0%	1%	2%

Care should be taken interpreting these data on motor loading. First, these are one-time instantaneous load measurements taken on systems where load may vary substantially on an hourly or seasonal basis. While our escorts reported that the measurements were made under typical operating conditions, we could not independently verify these reports. In addition, the readings are subject to some measurement error. The auditors were well trained in the use of the meters and the proper method of connecting a motor for measurement. However, in practice, the connection of leads and current transducers appropriate to current flow is substantially more difficult on the factory floor than it is under test conditions.

SATURATION OF EPACT-COMPLIANT MOTORS[11]

As of October 1997, all integral horsepower, polyphase, general purpose, low voltage AC induction motors from 1 to 200 horsepower sold in the U.S. must meet minimum efficiency standards. These standards, promulgated by the Energy Policy Act of 1992 (EPAct), are based on the National Electrical Manufacturers Association (NEMA) MG-1 Table 12-10. The minimum efficiency standard increases with horsepower category. The standards do not cover so-called Definite and Special Purpose motors,[12] nor do they cover integral horsepower motors over 200 horsepower. The motors covered by the standards account for 50–70 percent of all integral horsepower motors sold and 23–32 percent of annual energy consumed by integral horsepower motors.

11 In this report, the term "saturation" denotes the percentage of efficient equipment installed in the population. "Penetration" denotes the percentage of efficient equipment in the current stream of annual sales or shipments.

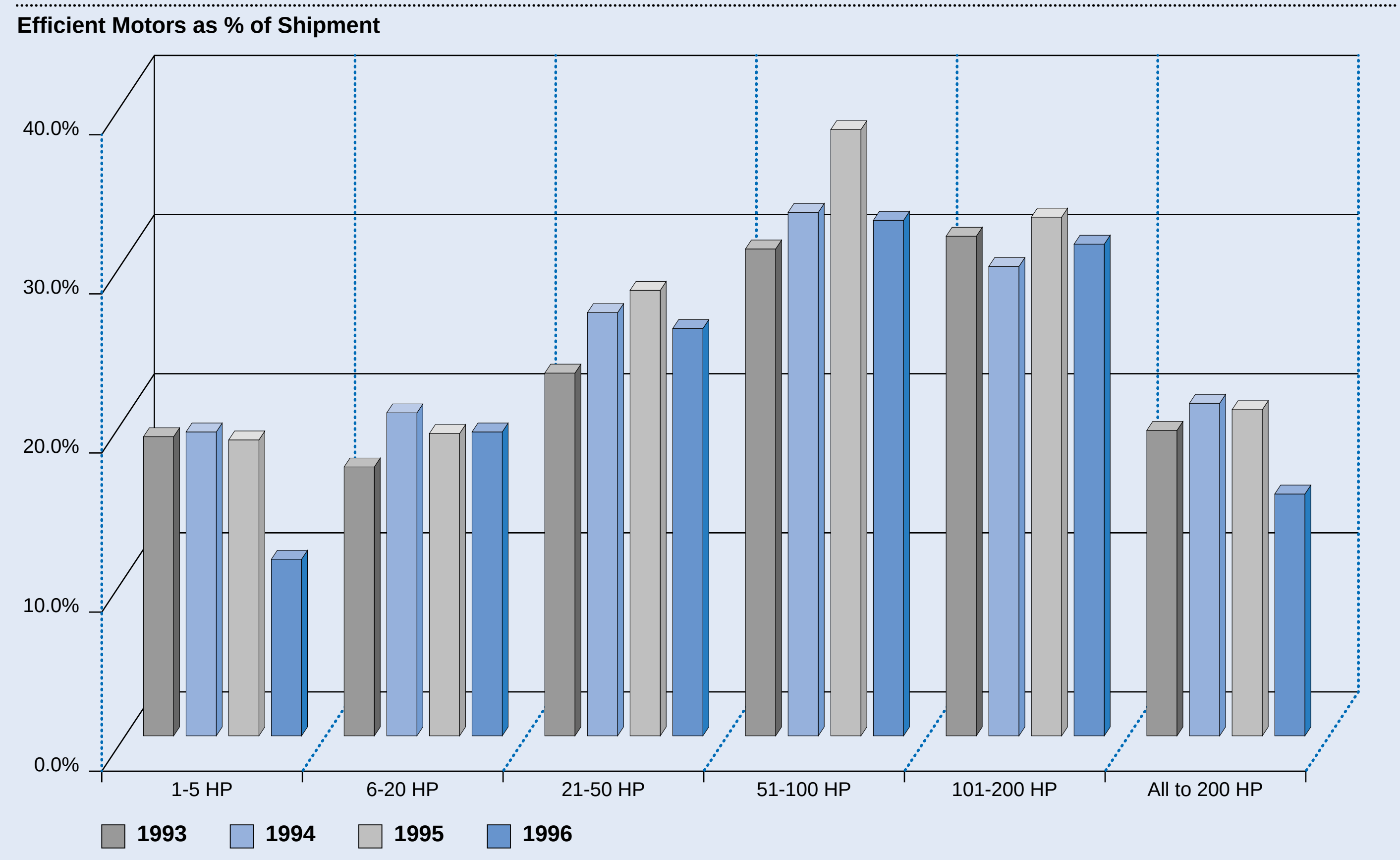
12 "Definite purpose" motors are defined by EPAct as motors that are designed in standard ratings and construction but cannot be used in most general purpose applications. "Special purpose" motors have special mechanical or operating characteristics designed for a specific application.

EFFICIENCY OF MOTORS SHIPPED

The Bureau of the Census has been tracking motor shipments and value of shipments by NEMA (now federal) efficiency designation since 1993. Most recent available figures run through 1996. Figure 1-5 shows the percentage of annual integral horsepower motor shipments represented by motors that met the NEMA (now EPAct) standards by year and by horsepower category. The following trends can be discerned.

- During the years 1993–1995, the market penetration of efficient motors held fairly steady around 20 percent, with the highest penetration in the 51–100 HP category.
- In 1996, the penetration of efficient motors declined to 15 percent. From 1995 to 1996, shipments of EPAct motors declined from 340,451 to 335,570. Shipments of standard efficiency motors increased 42% from 1.32 to 1.87 million units. Most of this increase came in the 1–5 horsepower range. The percentage of efficient motors dropped in all horsepower categories covered by EPAct, except for 6–20 HP, where the penetration of efficient motors held even.
- During the period 1993–1996, 1.2 million motors meeting the current EPAct standards were shipped by domestic manufacturers.

Figure 1-5: Efficient Motor Penetration



SATURATION OF ENERGY-EFFICIENT MOTORS

The inventory captured efficiency information for each motor observed. If the nominal efficiency of the motor appeared on the nameplate, it was entered on the data collection instrument. If no efficiency information was provided on the nameplate, we used a default value taken from the standard efficiencies listed in MotorMaster+ motor system management software.

The saturation of efficient motors is shown in Table 1-20. These results reflect the cumulative effects of the shipments of efficient motors. Overall, the inventory results show that about 1.1 million motors, or 9 percent of the population, meet or exceed the EPAct standards. The highest saturations are in Chemicals (SIC 28) and Paper (SIC 26), process industries with high levels of motor system energy consumption. Among the large motor system energy-using sectors, Primary Metals (SIC 33) has the lowest saturation of efficient motors.

The saturation of efficient motors is consistently greater for larger motors, with over 25 percent of motors of 101 to 200 HP meeting the EPAct standards. There are no standards for motors greater than 200 HP. However we estimated the saturation of energy-efficient motors over 200 HP by applying the EPAct efficiency standard for 200 HP motors. Using this benchmark, the saturation of efficient motors drops off for motors greater than 500 HP.

Table 1-20: Saturation of Efficient Motors by Horsepower Size: Manufacturing

Motor Horsepower	28 Chem	26 Paper	33 Metals	29 Petrol.	20 Food	Other	*All SICs Percent*	*All SICs Number*
1–5	7.8%	12.0%	2.1%	4.7%	6.6%	7.5%	***7.2%***	***523,735***
6–20	15.1%	17.3%	2.0%	8.3%	12.4%	10.3%	***10.4%***	***340,437***
21–50	21.6%	21.9%	4.3%	11.8%	13.2%	7.8%	***11.3%***	***127,111***
51–100	27.9%	27.2%	8.4%	2.1%	28.3%	15.3%	***17.1%***	***62,234***
101–200	32.7%	17.0%	0.1%	7.0%	7.4%	37.6%	***25.5%***	***56,247***
201–500	19.8%	4.2%	0.0%	19.6%	5.2%	48.4%	***17.7%***	***15,346***
501–1000	1.3%	0.0%	0.0%	0.0%	0.0%	9.5%	***1.3%***	***352***
1000+	4.5%	0.0%	9.6%	0.6%	0.0%	0.0%	***3.9%***	***425***
All Sizes	14.4%	15.3%	2.5%	7.5%	8.8%	8.9%	***9.1%***	***1,125,887***

SATURATION OF ADJUSTABLE SPEED DRIVES

Adjustable speed drives (ASDs), also referred to as variable speed drives, variable frequency drives, and adjustable frequency drives offer two major benefits to industrial end-users.

- Enhanced process control. ASDs allow factory managers to increase their control over production processes, thereby increasing consistency and quality.

By installing an ASD to the induced draft fans on this Basic Oxygen Furnace, Bethlehem Steel saved more than $600,000, showing the substantial savings that can be achieved through ASD applications.

- Energy savings. ASDs can be used to match the speed of an AC motor to the requirements of a fluctuating load, such as a pump that must move volumes of fluid that change in the course of a production shift. For centrifugal loads, which include many pumps and fans, power requirements are roughly proportional to the cube of the fluid velocity, which is proportional to motor speed over a wide range of operating conditions. Thus, the energy (and financial) penalty of running a pump or fan faster than necessary to accomplish the work at hand is severe. Conversely, the savings available through matching motor speed to system requirements can be very high.

Not all motor systems with fluctuating loads offer opportunities for cost effective capture of energy savings through the application of ASDs. In analyzing the saturation of ASDs for the purposes of this report, it is useful to understand the factors that favor cost effective applications. Generally speaking, these factors include:

- Horsepower. Generally, the higher the horsepower, the more likely the cost-effective application of ASDs.
- Operating hours. Generally, ASDs will be cost effective only on motor systems used 2,000 hours per year or more.
- Nature of load. Centrifugal loads, such as pumps and fans, offer the best potential savings. Reciprocating machines offer fewer opportunities.
- Load fluctuation. Loads that vary over time by 30 percent of full load offer the best opportunities for cost effective application.
- Circulating pumps versus systems with static head. In pumping, ASDs are applicable primarily to circulating systems as opposed to systems with significant static head. In the latter situations, slowing the pump may actually lead to higher energy use under certain conditions, as well as to severe maintenance problems.

CURRENT SATURATION OF ASDS

Table 1-21 shows the distribution of motor systems with ASDs by horsepower class. Currently, the saturation of ASDs is fairly low: 9 percent of motor systems which represent 4 percent of total motor system energy. The saturation of ASDs, both in terms of units and energy is highest in the smallest horsepower classes. In these cases, ASDs are likely to be used primarily to enhance control over production processes rather than to save energy.

Table 1-21: Saturation of Motor Systems with AC Adjustable Speed Drives by Horsepower Class

	Motor Systems with ASDs		Energy in Systems with ASDs	
Horsepower Class	**Number**	**% of Total**	**GWh/Year**	**% of Total**
1–5	767,807	11%	3,753	13%
6–20	254,862	8%	4,431	7%
21–50	46,126	4%	2,545	3%
51–100	13,536	4%	2,888	4%
101–200	11,661	5%	2,955	4%
201–500	1,873	2%	1,421	2%
501–1000	820	3%	3,127	4%
1000+	644	6%	4,203	5%
All Motor Systems	***1,097,328***	***9%***	***25,325***	***4%***

Table 1-22 shows the distribution of motor systems with ASDs by application. Over 80 percent of ASDs currently in use are installed in “other systems.” Motor system optimization studies conducted by Motor Challenge and consortia of U.S. and Canadian utilities have found that the largest energy savings for ASDs are present in fluid systems—pumps, fans, and compressors. Saturation of ASDs on pump and compressed air systems is particularly low, at present.

Table 1-22: Saturation of Motor Systems with ASDs by Application

	Motor Systems with ASDs		Energy in Systems with ASDs	
Application	**Number**	**% of Total**	**GWh/Year**	**% of Total**
Pump	77,510	3.2%	4,205	2.9%
Fan	101,204	7.3%	6,564	8.3%
Compressed Air	11,044	1.7%	3,354	3.7%
Other	907,570	11.4%	11,202	4.3%
All Applications	***1,097,328***	***8.8%***	***25,325***	***4.4%***

THE POTENTIAL MARKET FOR ASDS

We have used information collected in the inventory to develop an estimate of the size of the potential for cost-effective applications of ASDs in manufacturing motor systems of 1 HP or greater. We developed and applied a number of screening factors to identify motor systems in the inventory that would likely be good candidates for cost-effective retrofit with an ASD. These screening factors were developed in consultation with engineers familiar with field analyses of ASD applications and from review of ASD screening tools, such as ASD Master. (EPRI, 1996)

Engineers generally use a number of screening factors to assess whether installation of an ASD on an existing motor system will be cost-effective in terms of energy savings. Table 1-23 shows these factors along with relevant indicators developed from the inventory and our assessment of the reliability of the information from which the indicators are developed.

Table 1-23: ASD Applicability Criteria

Characteristic	Screening Factor for ASD Applicability	Indicators from the Inventory
1. Induction Motors	• Only AC motors can use an ASD (more specifically an adjustable frequency drive).	• Reliable observations of motor type for each motor system inventoried.
2. Horsepower	• <15 HP the payback is usually too long. • 15 to 30 HP are good candidates. • >30 HP usually excellent candidates for ASDs.	• Reliable observations of HP for each motor system inventoried.
3. Operating Hours	• Relatively high operating hours (> 2000 per year).	• Based on escorts' reports. Not directly observed. Medium confidence.
4. Type of Load	• Centrifugal load rather than a static load or constant volume displacement.	• Can be inferred in most cases from basic system description. All pumps and fans are classified as centrifugal loads.
5. Load Fluctuation	• Load variability greater than 30%, e.g., a load that varies from 60% to 90%.	• Obtained assessment from escort on whether load fluctuates for each system. No information on degree of fluctuation. Questionable confidence in accuracy.
6. Percentage of Time at Reduced Load	• The loading on a motor may vary a great deal but if the variation occurs for only a short period of time and it is running most of the time at a constant load, a drive is usually not justified.	• Not observed. Would require continuous load measurements.
7. Existing Load Modulation Equipment	• Throttle Valve: excellent applicability of ASDs. • Outlet Damper: good applicability of ASDs. • Inlet Vane: depends on the type of control. Iris type is better to retrofit with ASD than the parallel box type. • Multi Speed Motor: with a throttle valve it is also indicated. • Eddy Current Clutch: applicability fair but it may not pay back. • Adjustable Speed Gearbox: direct load measurements needed. • None: direct load measurements needed.	• Observed load modulation mechanisms for each inventoried system. • Reliability of observations questionable due to difficulties in finding and identifying control mechanisms in some cases.

We classified motor systems that met the first four conditions listed in Table 1-24 *and* were not currently equipped with ASDs as likely candidates for retrofit with an ASD. This subset is likely to be somewhat larger than the actual population of cost-effective applications because it does not take into account the final three screens. However, data on whether loads on individual machines fluctuated were of questionable reliability, and it was not possible under the constraints of the project to gather information on the degree of load fluctuation. Similar problems affected the observations of existing (non-ASD) load controls. We thus decided to proceed using screening variables in which we had a medium to high degree of confidence in identifying the potential market.

Table 1-24 displays the result of the first cut estimation of the remaining potential for cost-effective applications of ASDs to reduce energy use. The numbers to the right of the "Total" column represent the number of motor systems (top half of the table) and motor system energy (bottom half of the table) that met the four threshold criteria for successful ASD applications. These are: the system is driven by an AC motor, 21 HP or greater, for more than 2,000 hours per year, and currently is not equipped with an ASD. Roughly 7 percent (about 839,000 units) of the current population of integral horsepower motors meet these criteria. They represent 70 percent of total motor system energy. Motor systems that meet the further screening criterion of centrifugal loads (areas printed in blue) account for 3 percent of all units and 29 percent of total motor system energy.

Table 1-24: Distribution of Motor Systems with Good Potential for ASD Application

		AC Motor Systems with No ASD, 2000+ Hours over 20 HP				
HP Category	**Total**	**All Applications**	**Fans**	**Pumps**	**Air Comp.**	**Other**
Units						
1–5	7,306,080					
6–20	3,288,035					
21–50	1,129,527	500,058	73,969	135,654	91,807	198,629
51–100	363,940	176,662	17,509	56,745	24,621	77,787
101–200	220,908	104,406	18,417	17,269	18,122	50,598
201–500	86,836	41,897	1,958	8,526	11,916	19,496
501–1000	28,047	10,426	1,224	1,046	1,208	6,947
1000+	10,958	5,294	425	1,063	2,360	1,446
Total	***12,434,330***	***838,744***	***113,502***	***220,304***	***150,034***	***354,904***
Energy: GWh/Year						
1–5	27,807					
6–20	60,122					
21–50	73,111	60,331	9,807	22,433	7,321	20,770
51–100	72,924	61,044	8,020	23,616	5,752	23,656
101–200	83,099	68,559	13,331	18,693	9,035	27,500
201–500	90,819	72,041	6,103	22,860	15,624	27,454
501–1000	77,238	59,200	8,536	8,951	5,500	36,214
1000+	90,307	82,521	11,149	10,972	40,233	20,168
Total	***575,428***	***403,696***	***56,945***	***107,524***	***83,465***	***155,762***

Numbers printed in blue represent centrifugal loads.

The final step in assessing the magnitude of potential applications of ASDs is to gather and apply evidence regarding the effects of the final screens for load fluctuation. As discussed above, the patterns of response to items about load fluctuation in individual systems appeared questionable, especially when disaggregated to horsepower and end-use categories. For the population of motors as a whole, we found that 26 percent of the motor systems representing 19 percent of total motor system energy had fluctuating loads. Applying these factors to the results in the table above, the remaining "prime market" for ASDs as energy saving devices would total about 220,000 units which consume 78,000 GWh per year, or 14 percent of total motor system energy. This last estimate is consistent with expert opinion on the applicability of ASDs, as discussed in Section 2.

Section 2: Opportunities for Energy Savings

This section presents the methods by which potential motor system energy savings were calculated and summarizes the estimates. We begin with an overview of estimation methods and results. We then present a detailed description of the methods used on a measure-by-measure basis. The section concludes with a detailed description of the results of the energy savings estimates.

OVERVIEW OF SAVINGS ESTIMATION METHODS AND RESULTS

Estimates of potential energy savings available in a given population of facilities generally distinguish between a number of conceptual approaches. These can be summarized as follows.

- Technical potential denotes energy savings that can be achieved by applying proven energy efficiency technologies to all available opportunities for their use in the population, regardless of the relationship between implementation costs and savings.
- Economic potential denotes energy savings that can be achieved through a subset of the technically feasible efficiency improvements that meet specified economic criteria. These criteria are often expressed as simple payback (the ratio of estimated annual energy cost savings to the capital costs of the measure) or as financial metrics, such as return on investment or internal rate of return. These latter measures take the full range of the measure's operating costs and benefits into effect, as well as the measure's predicted useful life. The financial metrics also take into account the cost of capital. This supports comparison of the performance of investments in energy efficiency to the performance of other potential uses of capital.
- Market potential denotes the energy savings that can be achieved by a subset of economically cost-effective measures which analysts believe the market can deliver during the time horizon of the analysis. Supply-side constraints on the achievement of economic potential include lack of awareness of energy efficiency measures and design practices among engineers and conflicting economic incentives for manufacturers or distributors who are principally interested in equipment sales. On the demand side, constraints arise from the competing priorities for capital expenditures and plant maintenance resources.

The energy savings estimates presented in this report are best characterized as the economic potential for energy savings through the retrofit of the inventory of manufacturing facilities as they were operated at the time of the study (1997). In reviewing the energy savings analysis, the reader should keep the following in mind.

- Financial criteria. We applied the criterion of a 3-year payback to the energy efficiency measures included in the potential savings calculations. For simple motor replacements, we implemented this criterion using cost and savings information available in the MotorMaster+ software. For more complex measures involving improvements to whole systems, we relied on the judgment of consulting engineers and other experts to estimate what portion of the relevant load could be retrofitted with a given measure with a 3-year payback.

There is extensive literature on the shortcomings of simple payback as an investment decision criterion.[1] However, a number of studies have shown that commercial and industrial customers rarely apply more formal financial criteria to investments in energy efficiency.[2] The 3-year time period was chosen as a mid point in the range of financial performance that industry observers believed that industrial enterprises would find acceptable.

- Total population versus facility-level estimates. The energy savings estimates presented below represent totals for the entire population of industrial facilities. They take into account the extent to which measures have already been implemented and limitations on the use of measures for specific applications which may affect some but not all facilities in an industry. The energy savings opportunities in a given plant or system (in terms of percentage of total motor system energy use) may be much larger than the corresponding percentage for the population. The Showcase Demonstration projects supported by Motor Challenge achieved documented system-level savings of 6 to 59 percent of initial energy use, with an average savings of 33 percent.
- Savings in retrofit versus new applications. The energy savings estimates presented below do not include estimates of savings that could be achieved by applying best design practices (versus current standard practices) to the design of new systems. In such situations, the costs of implementing best practices are far less than they are in operating plants, which leads to far better financial returns on incremental investments in energy-efficient design in new versus retrofit applications.

CATEGORIES OF MOTOR SYSTEM EFFICIENCY MEASURES

For purposes of this study we defined two categories of motor system efficiency measures:

- Motor efficiency upgrades, which improve the energy efficiency of the motor driving a particular machine or group of machines.
- System efficiency measures, which improve the efficiency of a machine or group of machines as a whole. System efficiency can be improved by reducing the overall load on the motor through improved process or system design, improving the match between component size and load requirements, use of speed control instead of throttling or bypass mechanisms, and better maintenance to name just a few of the engineering strategies available.

The assessment identified individual measures for which energy savings were to be estimated through review of secondary literature and interviews with engineers, motor system manufacturers, and other industry observers. Table 2-1 presents definitions and descriptions of the measures covered by this study.

The descriptions for system efficiency measures represent general types of energy efficiency strategies. These descriptions were further refined for each major application category: pump systems, fan systems, compressed air systems, and other process systems. These more detailed measure descriptions are discussed on pages 57 to 62.

[1] See, for example, Fuller, Sieglinde K. and Petersen, Stephen R. 1995. *Life-Cycle Costing Manual for the Federal Energy Management Program.* Washington, D.C., U.S. Department of Commerce, National Institute of Standards and Technology, Chapter 1.

[2] In a recent study, the assessment team found that only 11 percent of commercial customers applied any kind of financial analysis to the selection of lighting equipment. (XENERGY 1998)

Table 2-1: Motor System Efficiency Measure Descriptions

Measure Category/Measure Name	**Measure Description**
Motor Efficiency Upgrade	
Efficient replacement	Replace motor currently in use with higher efficiency motor. Savings estimated for upgrades to two different standards: EPAct and CEE.
Improve rewinding practices	Follow rewinding protocols adopted by the Electrical Apparatus Service Association (EASA). Avoid rewind practices known to contribute to efficiency degradation such as the use of high temperatures to soften wire.
System Efficiency Measures	
Reduce system load requirements	This category encompasses a wide range of strategies such as widening pipe diameters to reduce resistance, straightening ducts, leveling process flows over time to reduce peak loads, and eliminating unnecessary by-passes. These strategies share a common result in reducing and/or leveling loads on motors, which open up opportunities for use of smaller or fewer motors in the system. Case studies of these kinds of projects report reductions of 5 percent to 60 percent of system energy.
Reduce or control motor speed	Reduction of speed to match load or use of ASDs to match speed to fluctuating loads can save a great deal of system energy due to the exponential relationship between shaft speed and energy. Case studies of ASD installations or mechanical speed reductions to replace throttling controls have found system savings in the range of 30 percent to 80 percent.
Match component size to load	Frequently motor systems are sized to accommodate the peak load expected for the system, with little or no allowance for the operation of the process at partial load. Various schemes can be used to serve part load while saving energy. These include staging of equipment, automatic shutdown, parallel systems, and downsizing. Estimated savings from these kinds of projects range from 5 percent to 30 percent.
Upgrade component efficiency	For most types of turbomachinery, relatively small savings are available by upgrading the inherent efficiency of components such as pumps, compressors, and auxiliaries. Analysts suggest that available savings range from 2 percent to 10 percent of system energy.
Maintenance	For some kinds of systems, in particular air compressors, conscientious maintenance can yield significant system savings due to plugging leaks and maintaining system balances. Savings from these measures can range from 2 percent to 30 percent of system energy.
Motor downsizing	This measure reduces the size of the motor to better match load within the motor's efficient operating range. It is included in System Efficiency Measures because it involves the balancing of system components with load rather than upgrading the efficiency of the motor itself.

SAVINGS ESTIMATION METHODS

Motor efficiency upgrades.

The assessment team estimated potential energy savings for motor efficiency upgrades by applying the savings formulas and input assumptions contained in the MotorMaster+ motor selection software to descriptive data on each motor system inventoried.

System efficiency measures.

Determining whether system efficiency measures apply to a particular motor system requires more data, time, and professional judgment than could be brought to bear in the course of the inventory. We therefore developed and implemented the following three-step process for estimating potential energy savings from the inventory data:

1. Estimate total energy usage by major application. We used the results of the inventory to estimate energy use by major application category: pumps, fans, air compressors, and other process systems.
2. Compile expert opinion and case studies on measure applicability and savings fractions. The assessment team solicited the opinions of industry experts—primarily consulting engineers, manufacturers' technical staff, and industry association representatives—regarding the percentage of systems to which various measures in the major application categories could be cost-

effectively applied. We also solicited their opinion on the average savings these measures could achieve, in terms of percentage of initial system energy use. We gathered similar information from case studies and other documents. Using this information, we formulated high, low, and midrange estimates of potential savings for each principal measure type within the major motor system application categories.

3. Calculate high, low, and midrange savings estimates. The savings estimates were calculated by applying the following formula:

$$\textit{Applicability}_{(High,Midrange,Low)} \times \textit{Average Savings Fraction} \times \textit{System Energy.}$$

To estimate the potential savings from motor downsizing, we first estimated the savings available from downsizing the motors operating at less than 40 percent part load in the subsample of motors for which load measurements were made. We then projected these results to the population using the weighting procedures established through the site and motor sampling process.

Distribution of potential savings by type of measure.
Table 2-2 shows how potential savings are distributed among different kinds of measures and end uses in manufacturing only. Potential motor system energy savings in the manufacturing sector total between 61 billion and 104 billion kWh per year, with a midrange estimate of 85 billion kWh per year. The savings in the major groups of measures are additive. Potential efficiency improvements in non-manufacturing facilities are estimated to add another 14 billion kWh in annual savings. These savings are not shown in Table 2-2.

Table 2-2: Summary of Motor Energy Savings Opportunities by Measure in Manufacturing Facilities

	Potential Energy Savings GWh/Year			Midrange Savings as Percent of	
Measure	Low**	Midrange**	High**	Total Motor System GWh	System-Specific GWh
Motor Efficiency Upgrades*					
Upgrade all integral AC motors to EPAct Levels***		13,043		2.3%	
Upgrade all integral AC motors to CEE Levels***		6,756		1.2%	
Improve Rewind Practices		4,778		0.8%	
Total Motor Efficiency Upgrades		24,577		4.3%	
Systems Level Efficiency Measures					
Correct motor oversizing	6,786	6,786	6,786	1.2%	
Pump Systems: System Efficiency Improvements	8,975	13,698	19,106	2.4%	9.6%
Pump Systems: Speed Controls	6,421	14,982	19,263	2.6%	10.5%
Pump Systems: Total	15,396	28,681	38,369	5.0%	20.1%
Fan Systems: System Efficiency Improvements	1,378	2,755	3,897	0.5%	3.5%
Fan Systems: Speed Controls	787	1,575	2,362	0.3%	2.0%
Fan Systems: Total	2,165	4,330	6,259	0.8%	5.5%
Compressed Air Systems: System Eff. Improvements	8,559	13,248	16,343	2.3%	14.6%
Compressed Air Systems: Speed Controls	1,366	2,276	3,642	0.4%	2.5%
Compressed Air Systems: Total	9,924	15,524	19,985	2.7%	17.1%
Specialized systems: Total	2,630	5,259	7,889	0.9%	2.0%
Total System Improvements	36,901	60,579	79,288	10.5%	
Total Potential Savings	***61,478***	***85,157***	***103,865***	***14.8%***	

* Potential savings for Motor Efficiency Upgrades calculated directly by applying engineering formulas to Inventory data.
** High, Medium, and Low savings estimates for system efficiency improvements reflect the range of expert opinion on potential savings.
***Includes savings from upgrades of motors over 200 HP not covered by EPAct standards.

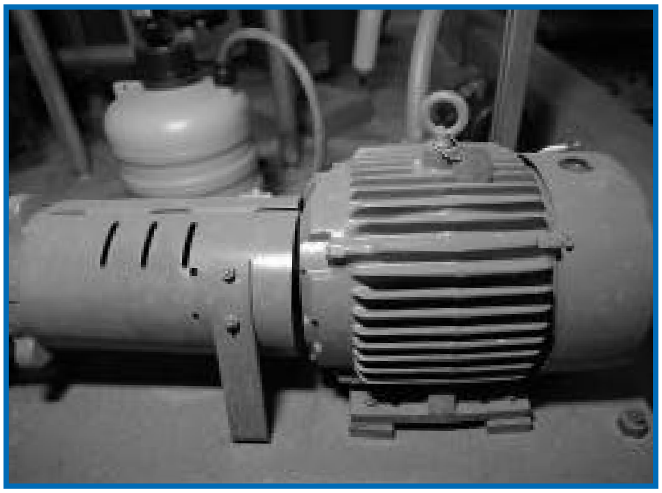
Nearly two-thirds of all potential savings derive from system efficiency measures, such as the substitution of adjustable speed drives for throttling valves or bypass loops in pumping systems or fixing leaks in compressed air systems. The specific system efficiency measures for which savings were estimated differ for each major application category. For convenience of presentation, the specific measures have been collapsed into two categories: System Efficiency Improvements and Speed Control. Detailed descriptions of these measures appear below. Savings attributable to the major industrial fluid systems—pumps, fans, and air compressors—present between 45 and 62 percent of the total savings opportunities, taking into account low and high estimates.

DETAILED ENERGY SAVINGS ESTIMATION METHODS

SYSTEM EFFICIENCY MEASURES

For each of the major fluid processes—pumps, fans and air compressors—we developed estimates of the percentage of load to which individual measures were applicable and the expected savings from the measures. As discussed above, we compiled lists of specific measures applicable to each fluid process from secondary literature and interviews with industrial engineers. We then developed preliminary estimates of applicability and savings fraction from the literature and case studies. The preliminary estimates were then circulated to groups of individuals expert in particular applications and technologies. We revised the preliminary estimates based on comments from the expert reviewers. The tables of assumptions below summarize the results of this process.

Pump system energy efficiency can be improved by 20%, on average, across U.S. industry with a variety of system efficiency measures.



PUMP SYSTEMS

The pump system savings have been developed based on information from several sources. Descriptions of the types of system improvements applicable to pumps for each measure category are contained in Table 2-3.

Table 2-3: Assumptions on Pump System Efficiency Measures

Measure	Sources and Method to Determine Applicable Load and Savings Fraction
Reduce Overall System Requirements	
Equalize flow over production cycle using holding tanks.	Easton Consultants[3] report suggests savings are in the 10–20 percent range.
Eliminate bypass loops and other unnecessary flows.	Easton report suggests savings are in the 10–20 percent range.
Increase piping diameter to reduce friction.	The retrofit of increasing pipe diameter has been done in 9 percent of facilities according to the practices survey. This is an expensive measure but the Easton report suggests savings are in the 5–20 percent range. This is corroborated by specialists in the pulp and paper industry.[4]
Reduce “safety margins” in design system capacity.	This measure is applicable to all pumps. Easton report suggest savings are in the 5–10 percent range.

(Table continues on next page)

[3] Easton Consultants, *Strategies to Promote Energy-Efficient Motor Systems in North America’s OEM Markets.* Stamford, Connecticut. Easton Consultants, Inc. 1995.

[4] Personal communications with R. Giese.

Table 2-3: *Continued*

Measure	Sources and Method to Determine Applicable Load and Savings Fraction
Match Pump Size to Load	
Install parallel systems for highly variable loads.	According to the practices survey 5 percent of facilities have implemented parallel pumps. Easton report suggest savings are in the 10–50 percent range. Other experts[5] report that the "best practice" for variable loads is to install a larger pump with speed control to obtain similar savings.
Reduce pump size to better fit load.	According to the practices survey 5 percent of facilities have implemented smaller pumps. Easton report, supported by other experts, suggests that pumps are routinely 15–25 percent oversized.[6]
Reduce or control pump speed	
Reduce speed for fixed loads: trim impeller, lower gear ratios.	According to the inventory data, 82 percent of pumps have load modulation recorded as "none." Performance optimization studies cite savings as high as 75 percent in the food processing, paper and petrochemical industries.
Replace throttling valves with speed controls to meet variable loads.	According to the inventory data, 6 percent of pumps have load modulation recorded as "throttle valve," which seems low according to industry experts. Case studies of ASD installations show savings in the range of 30 to 80 percent.[7] This measure applies to circulating pump systems, not systems with static heads.
Improve Pump Components	
Replace typical pump with most efficient model, or one with an efficient operating point better suited to the process flows.	According to the inventory data, 16 percent of pumps are greater than 20 years old, many of which can be replaced with more efficient models that better match the process operating point. According to industry experts, the problem is not necessarily the age of the pump but the fact that the process may have changed over time and that the operating point does not match the best efficiency point of the pump. Easton report notes pump efficiency may degrade 10–25 percent before replacement. Newer pumps are 2–5 percent more efficient. ACEEE[8] cites savings in the 2–10 percent range.
Replace belt drives with direct coupling.	According to the inventory data, 4 percent of pumps have drive type as V-belt, many of which can be replaced with direct couplings. Savings are on the order of 1 percent
Operation and Maintenance	
Replace worn impellers, especially in caustic or semi-solid applications. Inspect and repair bearings, lip seals, packings and other mechanical seals.	According to the Hydraulic Institute[9], pump efficiency degrades from 1 to 6 points for impellers less than maximum diameter and with increased wear ring clearances. Pumps less than 15 HP are particularly sensitive to reductions in pump efficiency due to mechanical losses.

Based on the information summarized in Table 2-3, we developed estimates of the applicability and savings fractions for pump system efficiency measures. These are shown in Table 2-4. This table and the corresponding tables for fan and air compressor efficiency measures have been reviewed by a panel of engineers and industry experts. They represent our best estimates of savings potential for pump, fan, and compressed air systems. Note that the greatest savings for pump systems relate to controlling pump speed. This is consistent with expert opinion that circulating pumps are generally good candidates for ASDs.

[5] Personal communication with Robert W. Bailey at Planergy, Richmond, CA, October 30, 1997.

[6] Personal communication with Gunnar Hovstadius, ITT Flygt, Trumbull, CT.

[7] Unpublished data, Wisconsin Performance Optimization Service Program.

[8] Elliot, R. Neal. *Electricity Consumption and the Potential for Electric Energy Savings in the Manufacturing Sector.* Washington, D.C. ACEEE 1994.

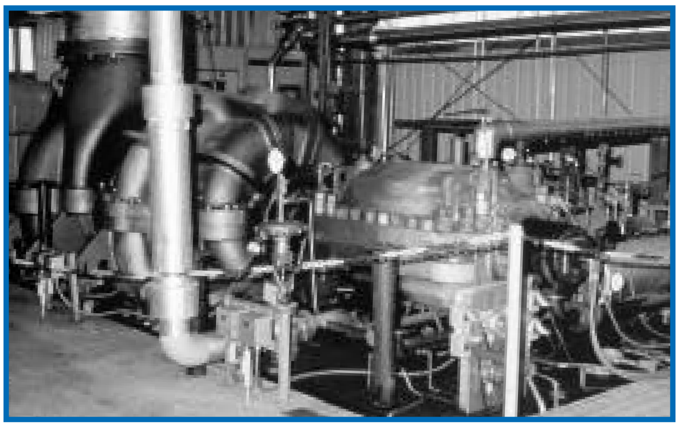
[9] Hydraulic Institute. *Efficiency Prediction Method for Centrifugal Pumps.* Parsippany, NJ. 1994.

Table 2-4: Pump System Improvement Applicability and Savings

Measure	Applicability Low	Applicability Midrange	Applicability High	Savings Fraction	Net Savings
Reduce Overall System Requirements	40%	50%	65%	10%	5.0%
Match Pump Size to Load	10%	20%	30%	20%	4.0%
Reduce or Control Pump Speed	15%	35%	45%	30%	10.5%
Improve Pump Components	5%	10%	15%	5%	0.5%
Operation and Maintenance	2%	5%	7%	2%	0.1%
Overall Savings					***20.1%***

COMPRESSED AIR SYSTEMS

The air compressor system savings have been developed based on information from several sources. These include the *Improving Compressed Air System Performance Sourcebook* developed by the Compressed Air Challenge initiative and published by the Motor Challenge Program, as well as numerous engineering texts and case studies. The types of system improvements applicable to air compressors for each measure category are described in Table 2-5. While the measures mentioned are not applicable to all situations, they serve as a guide to make generalized estimates of the relative applicability of measures and the savings associated with them.



Compressed air systems like this one can be improved by 17%, on average, and will save U.S. industry up to $1 billion per year.

Table 2-5: Compressed Air System Efficiency Measures

Measure	Sources and Method to Determine Applicable Load and Savings Fraction
Reduce Overall System Requirements	
Reduce overall system pressure through better system design and better ancillary components (filters and dryers).	According to the practices survey 15 percent of facilities have reconfigured piping and filters in their compressor systems. Easton report estimates savings in the range of 4–6 percent.
Reduce system demand by eliminating poor applications of compressed air.	The misapplication of compressed air for uses such as blowing, cooling, cleaning or to move parts, etc. is a wasteful practice. Compressed air can be replaced with blowers, fans or electric motors with substantial energy savings. Industry experts estimate that discontinuing these practices as well as shutting off air flow to equipment not in use can save as much as 20 percent.
Segment system and provide satellite or booster compressors or storage when remote locations have special requirements such as higher pressures, cleaner air, or short term high volumes.	While decentralizing compressors does not always save energy, some facilities with large compressors serving all departments in a relatively large area (in terms of floorspace) may benefit from segmenting the system. ACEEE report cites a case study in a Ford plant in which savings of 80 percent were achieved but industry experts[10] point out that this is not typical and savings are closer to about 5 percent.
Improve supply conditions; use outside air.	Assume half of all compressors use room air for supply. Easton report estimates savings for this measure in the range of 4–6 percent. Industry experts note that this measure may increase O&M.

(Table continued next page)

10 The authors grateful acknowledge the contributions of the following individuals in preparing this table: Lawrence Ambs, University of Massachusetts; Aimee McKane, Lawrence Berkeley National Laboratory; Dean Smith, Plant Air Engineering; Robert Bailey, Planergy; Chris Beals, David MacCulloch, and Mac Mottley.

Table 2-5 *Continued*

Measure	Sources and Method to Determine Applicable Load and Savings Fraction
Match Compressor Size to Load	
Size compressors for efficient trimming.	Stage compressors so that the base load is supplied by compressors running at design load with a trim compressor (reciprocating or rotary screw type) to supply the variable load. Industry experts estimate savings of 5 percent.
Compressor Control	
Install standard part load controls which include automation and storage.	This can be applied to most compressors. ACEEE cites savings in the 3–7 percent range.
Install microprocessor controls on compressor system.	These controls tighten the deadband from 10 psi to 2 psi. Savings in the 2–4 percent range.
Use parallel compressors and install multi-unit controls to reduce compressor part loading.	According to the practices survey 14 percent of facilities indicated using parallel compressors and 7 percent of facilities indicated the installation of multi-unit controls. Unloading controls were recommended for 6 of 7 case studies using AIRMaster[11], with savings ranging from 3 to 33 percent. Performance optimization studies calculate savings in the range of 11–16 percent. Easton study cites savings of 10–15 percent. Industry experts point out that these savings can only be achieved in facilities having several compressors, not just two or three.
Install ASDs for rotary compressors.	The inventory data indicates that 97 percent of compressors do not have ASDs. Easton estimates the proportion of rotary compressors is 72 percent. Industry experts point out that the opportunities may not be as large as these saturations suggest because there are often better methods to manage the load (sizing and trimming). For rotary compressors with variable loads ASDs offer better part load efficiency than inlet valve modulation. Savings are on the order of 10 percent according to industry experts.
Improve Compressor Components	
Replace older single stage reciprocating compressors and symmetrical screw compressors with more efficient model.	According to the inventory data, 6 percent of compressors are greater than 20 years old. Easton report cites a 10–20 percent efficiency variation across compressor types. Industry experts note that some of the older equipment, such as double acting reciprocating compressors, are very efficient.
Operation and Maintenance	
Reduce leaks by instituting an ongoing program of system maintenance on regulators, quick connect fittings, tubing, pipes and other points of connection.	According to the practices survey 38 percent of facilities indicated they had fixed leaks in the past 2 years. Easton report estimates savings in the range of 15–25 percent. ACEEE report states leaks are 15 percent of compressor load. All 7 case studies using AIRMaster recommend reducing leaks with estimated savings ranging from 2.7 to 59 percent.
Improve maintenance on compressor: e.g., valves for reciprocating compressors and intercoolers for centrifugal compressors.	Industry experts estimate savings in the range of 2–5 percent.
Change compressor filters and point of use filters regularly to reduce pressure drops.	Easton report cites that improved ancillary equipment saves 4–6 percent. Industry experts estimate that replacing point of use filters saves 3 percent and compressor filters 1–2 percent.

Using information contained in Table 2-5, we estimated the applicability and savings fractions of compressed air system efficiency measures. These are shown in Table 2-6. The greatest savings opportunity for compressors, representing half of the potential is to reduce the overall system requirements.

[11] Bonneville Power Administration, Case Studies: Compressed Air System Audits Using AIRMaster, January 1997.

Table 2-6: Compressed Air System Improvement Applicability and Savings

Measure	Applicability			Savings Fraction	Net Savings
	Low	Midrange	High		
Reduce Overall System Requirements	20%	30%	40%	20%	6.0%
Match Compressor Size to Load	5%	10%	15%	3%	0.3%
Compressor Control	15%	25%	40%	10%	2.5%
Improve Compressor Components	5%	15%	20%	5%	0.8%
Operation and Maintenance	50%	75%	85%	10%	7.5%
Overall Savings					***17.1%***

FAN SYSTEMS

This Louisiana Pacific low-cost fan optimization project achieved electrical cost savings of $85,000. Fan system improvements yield net savings of 5.5%.

The fan system savings have been developed based on information from several sources. The types of system improvements applicable to fans for each measure category are described in Table 2-7.

Table 2-7: Fans System Efficiency Measures

Measure	Sources and Method to Determine Applicable Load and Savings Fraction
Reduce Overall System Requirements	
Reduce “system effect” through better inlet and outlet design.	Easton report states that reducing system effect can reduce energy consumption by 25 percent.
Reduce fan oversizing.	Easton report states that cost pressures limit oversizing, but that reducing oversizing can reduce consumption by 1–5 percent. Industry experts[12] indicate that most have some degree of oversizing. It is often easier to control speed or use a slower speed motor than to replace fan with smaller size.
Reduce or control fan speed	
Replace inlet or outlet dampers and variable inlet vane with electronic speed controls to meet variable loads.	According to industry experts, there are about 10 times more fans with inlet damper than outlet damper, both of which allow some adjustment in flow. Performance optimization studies estimate savings in the range of 14–49 percent when retrofitting with an ASD. Higher savings are achieved with outlet damper but there are fewer applications.
Improve Fan Components	
Replace Standard V-Belt with Cogged V-Belt.	According to the inventory data, half of fans have “V-belt” drive type. According to Easton report, 2/3 of V-belts are standard and can be upgraded to cog belts. Standard V-belt efficiency ranges from 90–97 percent while cogged V-belt efficiencies are 94–98 percent.
Replace fan with more efficient model.	According to the Easton report, although fan efficiencies vary significantly across impeller types, there are limited opportunities to trade up to more efficient models.
Operation and Maintenance	
Improve O&M practices: • Tighten belts • Clean fans • Change filters regularly	These practices can be applied to all fans with savings ranging from 2 to 5 percent.

12 The authors acknowledge the contributions of Robert W. Bailey of Planergy in preparing this table.

The values used in the analysis for the applicability and savings fractions for fan systems are shown in Table 2-8.

Table 2-8: Fan System Improvement Applicability and Savings

Measure	Applicability: Low	Applicability: Midrange	Applicability: High	Savings Fraction	Net Savings
Reduce Overall System Requirements	5%	15%	25%	10%	1.5%
Reduce or Control Fan Speed	5%	10%	15%	20%	2.0%
Improve Fan Components	15%	20%	25%	5%	1.0%
Operation and Maintenance	25%	50%	60%	2%	1.0%
Overall Savings					***5.5%***

OTHER PROCESS SYSTEMS

Because the motor systems grouped under "Other Process Systems" are so diverse, we did not feel it would be appropriate to apply to them the savings estimation process described above. Rather, we applied the method for speed control measures alone, which are widely applicable to many kinds of motor systems. We selected an applicability factors ranging from 5 to 15 percent, which reflect the range indicated by our analysis of the potential market for ASDs presented in Section 1. Because we were not able identify and analyze all the applicable measures for other process systems, the potential savings for this category is likely to be somewhat underestimated.

MOTOR DOWNSIZING

Instantaneous load measurements were taken for a sample of up to 12 motors at each site. The results of these measurements are discussed and shown on pages 45-46. In general, the operating efficiency of a motor decreases significantly at part loads less than 40 percent. Motors that are consistently under loaded can be replaced with smaller motors. The smaller motor will run closer to its higher full load efficiency and as a result will consume less energy. Using the load measurement data, we estimated the potential savings from motor downsizing for the population as a whole.

The savings from downsizing are based on the difference in operating efficiency of motors in specific horsepower categories at 25 percent load and 75 percent part load. (For purposes of this estimate, we assume that oversized motors are running at an average of 25 percent part load and that the properly sized motors will run at 75 percent part load.) The savings fractions are calculated based on information contained in the MotorMaster+ software on the operating efficiency of standard motors at 25 percent part load and a smaller "downsized" motor at 75 percent part load. These efficiencies are shown in Table 2-9.

The difference in efficiency ("Savings Fraction" in Table 2-9) is multiplied by the energy consumption of the portion of motors operating below 40 percent part load in each horsepower category to obtain an estimate of potential annual energy savings. This is a simplification for several reasons. First the energy consumption for the baseline is calculated using the full load efficiency and average loading on the motor. Secondly, the savings fraction is based on the average part load efficiencies of motors in the same size category; however, the difference in efficiency at 25 and 75 percent part load of particular sized motors within a category varies greatly, especially for motors less than 10 horsepower. Nevertheless, the estimated savings will be a good indicator of the magnitude of downsizing savings relative to other measures.

Table 2-9: Part Load Efficiencies for Downsizing

Motor Size Category (HP)	Average Efficiency at 75% Load	Average Efficiency at 25% Load	Savings Fraction (%)
1–5	77.7%	64.7%	16.8%
6- 20	84.5%	81.7%	3.2%
21- 50	88.3%	86.8%	1.7%
51- 100	89.9%	87.9%	2.2%
101- 200	91.6%	89.1%	2.7%
201- 500	92.3%	90.3%	2.2%
501- 1000	92.3%	90.3%	2.2%
1000+	92.3%	90.3%	2.2%

Source: MotorMaster+.

MOTOR EFFICIENCY UPGRADES

EFFICIENT REPLACEMENT

As of October 1997, all integral horsepower, polyphase, general purpose, low voltage AC induction motors from 1 to 200 horsepower sold in the United States will have to meet minimum efficiency standards. These standards, promulgated by the EPAct, are based on the NEMA MG-1 Table 12-10. The minimum efficiency standard increases with horsepower category. The minimum EPAct standards leave room for improvement in motor efficiency and offer the opportunity for energy savings. As Figure 2-1 shows, some so-called "premium efficiency" motors currently on the market are more efficient than the minimum standard, particularly in the lower horsepower ranges.

Replacing standard efficiency, general purpose, three-phase, AC induction motors in use with EPAct energy efficiency rated motors could save U.S. industry over $500 million annually, and could reduce motor system energy consumption by 2.3%, on average.

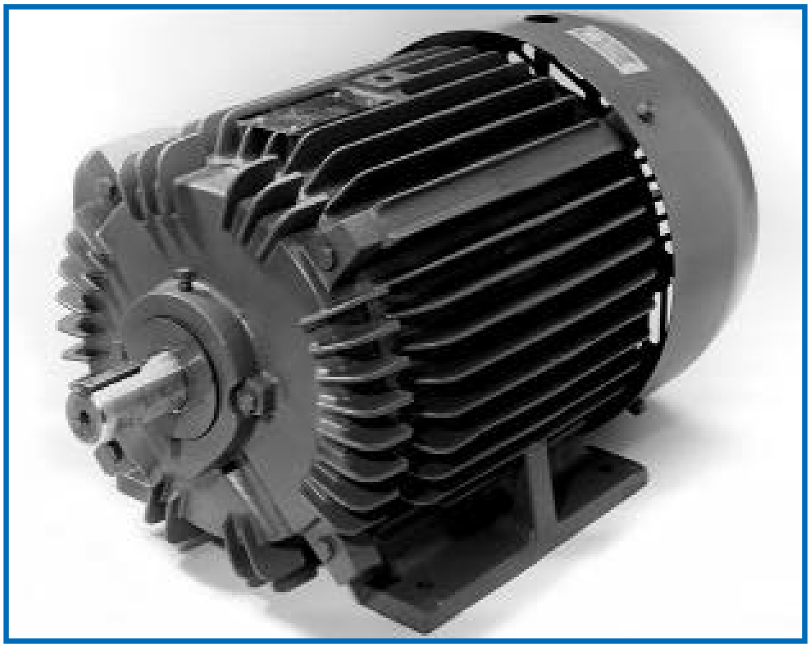
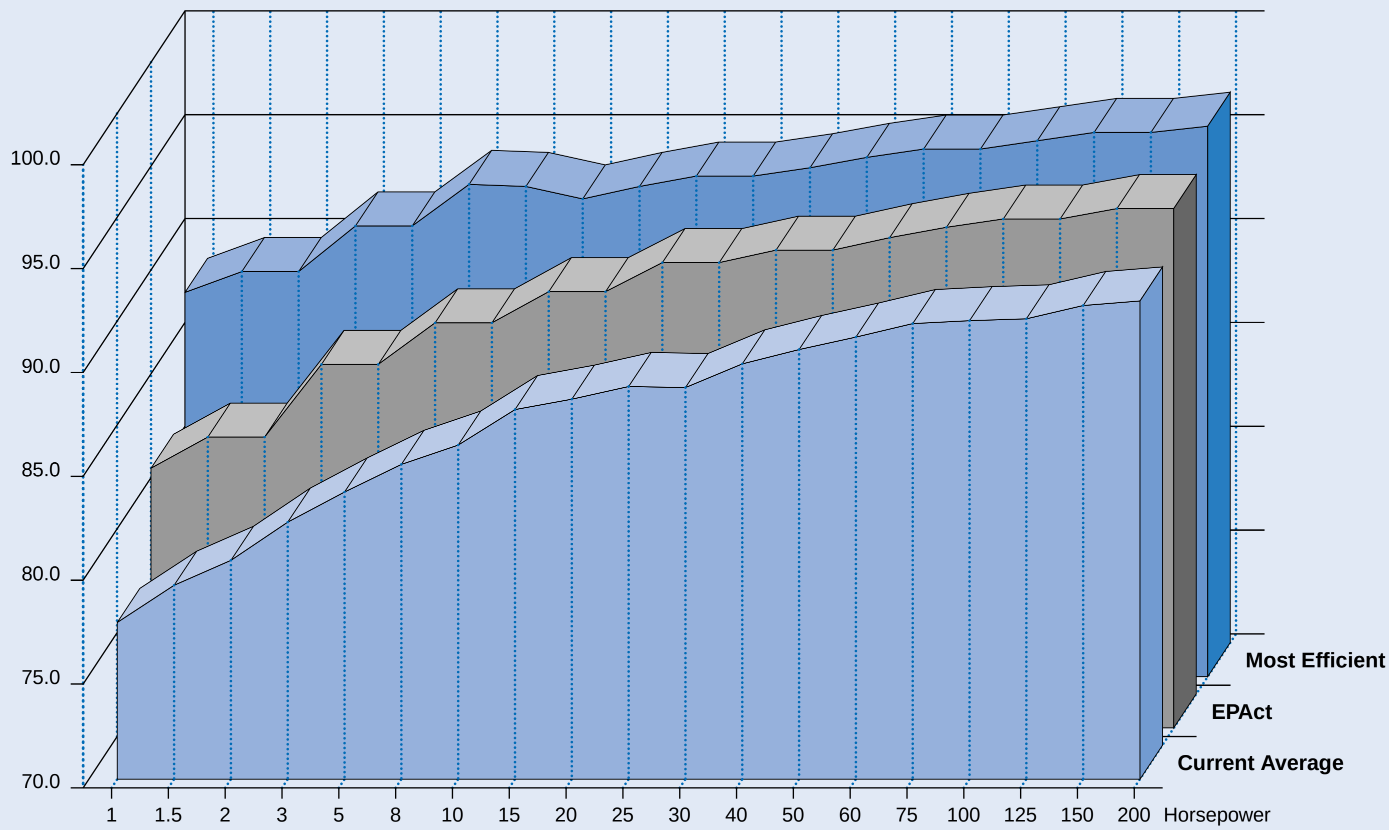


Figure 2-1: Comparison of Nominal Motor Efficiencies by Horsepower



The energy savings from replacing existing motors with their high efficiency equivalent are calculated based on energy consumption of the current motor compared to consumption of a motor meeting the efficiency requirements of EPAct, or alternatively, a higher efficiency standard advanced by the Consortium for Energy Efficiency (CEE). Energy savings are calculated by taking the difference in energy consumption of the baseline motor and the energy consumption of the high efficiency equivalent motor. The equation to calculate savings is:

$$\textit{Energy Savings} = \textit{Annual Energy}_{base} - \textit{Annual Energy}_{higheff.}$$

where $\textit{Annual Energy}_{base}$ refers to the energy consumption of existing baseline motor and $\textit{Annual Energy}_{higheff.}$ refers to the energy consumption of the equivalent high efficiency motor. The equation for annual energy is as follows:

$$\textit{Annual Energy} = \frac{\textit{horsepower} \times 0.746 \times \textit{operating hours} \times \textit{motor loading}}{\textit{efficiency}}$$

The value of the efficiency parameter is the only parameter that changes in calculating the baseline and high efficiency motor consumption. The baseline efficiency used in the equation is taken from the nameplate reading gathered in the survey. Where the nameplate efficiency is missing or otherwise inaccessible, a default efficiency is used, taken from the standard efficiencies listed in MotorMaster+ motor energy system management software. The default, EPAct standard, and CEE standard efficiencies used in the calculation for 1800 rpm motors are shown in Table 2-10.

IMPROVED REWINDING PRACTICES

The motor practices survey results indicate that 79 percent of the sites rewind some of their motors upon failure. The efficiency of a rewound motor is often poorer than the efficiency of the motor when new. Many studies have been performed to measure the effect of rewinding on motor efficiency.[13] Generally the studies involve taking performance measurements on a small number of motors before and after rewinding. In some cases, the rewinds have been performed "blind" by commercial shops using their standard practices. In others, specific technical protocols were covered. The results of the studies vary widely, with average degradation in efficiency after the rewinds ranging from 0 to 2.5 efficiency percentage points. Generally, researchers have found that use of low burn-out temperatures to remove old windings and careful attention to the original winding pattern can minimize efficiency degradation. However, the measured effects of these procedures have not been consistent. We should also note that operating efficiency testing procedures have a resolution of 0.2 efficiency percentage points.

If improperly done, rewinding can reduce the efficiency of motors 1% to 2%.

Given these findings, we assigned a savings fraction of 1.0 percent (0.9 percent difference in efficiency degradation between best practice and conventional rewinds divided by 90 percent initial efficiency). The annual energy savings from using best rewinding practices was then calculated using the following equation for the motors in each horsepower category of the inventory:

$$\textit{Energy Savings} = \textit{Annual Energy}_{base} \times \textit{Fraction Failed}_{year} \times \textit{Proportion Rewind} \times \textit{Savings Fraction.}$$

Table 2-10: Motor Efficiencies Used in Savings Calculations

Horsepower Range	Default	EPAct	CEE
Up to 1 HP	77.55	82.5	86.5
>1 to 1.5	79.34	84.0	86.5
>1.5 to 2	80.54	84.0	86.5
>2 to 3	82.38	87.5	89.5
>3 to 5	83.83	87.5	89.5
>5 to 7.5	85.16	89.5	91.7
>7.5 to 10	86.09	89.5	91.7
>10 to 15	87.80	91.0	92.4
>15 to 20	88.30	91.0	93.0
>20 to 25	88.91	92.4	93.6
>25 to 30	88.86	92.4	93.6
>30 to 40	90.00	93.0	94.1
>40 to 50	90.69	93.0	94.5
>50 to 60	91.29	93.6	95.0
>60 to 75	91.94	94.1	95.4
>75 to 100	92.08	94.5	95.4
>100 to 125	92.17	94.5	95.4
>125 to 150	92.81	95.0	95.8
>150 to 200	93.03	95.0	96.2

[13] See Howe et al. (1993) Drivepower Technology Atlas, E-Source, Boulder, CO, Section 10 for a summary of these studies.

The sources for the parameters in this equation are as follows:

- *Annual Energy$_{base}$* is developed through the inventory data. See Section 1.
- *Fraction Failed* is estimated by dividing average lifetime operating hours for motors in the horsepower category (Seton, Johnson & Odell, 1987) by the average annual hours of operation for motors in the horsepower category (see Table 1-16).
- *Proportion Rewound* is estimated from the results of the Practices Inventory.
- *Savings Fraction* is set to 1.0 percent. See discussion above.

Table 2-11 contains the key input and results of the savings fraction estimates for improved rewinding practices. The savings estimate for all other measures discussed in this section assume that the measure will be implemented for all applicable systems in the population. In the case of improved rewinding practices, it is more "realistic" to characterize the measure as applying to the fraction of motors that fails in a year, even though, over a number of years, it will apply to all motors that are rewound. To characterize the magnitude of potential savings from improved rewinding practices on the same basis as the other measures, we have also calculated the savings associated with going through a full "rewind cycle" for all motors in the inventory. Full cycle savings range from 0.20 to 0.91 percent of total motor system energy consumption, depending on horsepower category. They increase with horsepower size because the percentage of motors rewound increases with size.

Table 2-11: Savings Fractions for Improved Rewinding Practices

HP Category	Mean Lifetime Operating Hrs	Mean Annual Operating Hrs	% of Units Failed/Year	% of Failed Units Rewound	Full Cycle Savings % of Total Energy	Savings/Year % of Total Energy
1-5	40,000	2,745	7%	20%	0.20%	0.01%
6-20	40,000	3,391	8%	61%	0.61%	0.05%
21-50	40,000	4,067	10%	81%	0.81%	0.08%
51-100	40,000	5,329	13%	90%	0.90%	0.12%
101-200	40,000	5,200	13%	91%	0.91%	0.12%
201-500	40,000	6,132	15%	91%	0.91%	0.14%
501 -1000	40,000	7,186	18%	91%	0.91%	0.16%
1001+	40,000	7,436	19%	91%	0.91%	0.17%

ENERGY SAVINGS RESULTS

Table 2-12 summarizes total potential motor system energy savings by measure category and horsepower range. In the detailed tables on the following page, we include only the midrange estimates for savings from system efficiency measures. The greatest savings potential lies with the system savings measures, specifically in compressed air and pump systems. System improvements account for 71 percent of total potential motor system energy savings. System efficiency measures related to pumps fans and compressors account for 57 percent of total potential savings. The next largest opportunity for savings is for motor efficiency upgrades with motor downsizing and improved rewinding practices having the smallest savings potential. On an aggregate basis, energy savings opportunities are distributed fairly evenly across the horsepower size ranges. We should note, however, that the higher horsepower ranges contain many fewer motor systems than the lower ranges, and that the savings and required investment per system are correspondingly higher in the larger horsepower categories. Details of the savings estimates for each measure are described on the following pages.

Table 2-12: Overall Motor System Savings

	System Efficiency Measure Savings (GWh/Year)					Motor Eff. Upgrades	
Size Category (HP)	**Fan Systems**	**Pump Systems**	**Compressed Air Systems**	**Other Process Sys.**	**Downsize Motors**	**Efficient Replacement**	**Rewinds Improved**
1–5	226	1,312	107	331	1,973	1,824	56
6–20	603	3,804	409	557	953	2,972	367
21–50	584	4,882	1,422	597	459	2,767	592
51–100	470	5,268	1,090	636	753	2,213	656
101–200	776	4,204	1,599	774	559	2,105	756
201–500	354	4,825	2,690	892	749	2,617	826
501–1000	480	2,181	1,324	998	575	2,618	703
1000+	837	2,205	6,884	475	765	2,683	822
All Motors	***4,330***	***28,681***	***15,524***	***5,259***	***6,786***	***19,799***	***4,778***

SAVINGS FROM SYSTEM EFFICIENCY MEASURES

Table 2-13 shows estimates of energy savings from system efficiency measures by SIC. The key conclusions that can be drawn from this table are as follows.

- In the manufacturing sector, potential motor system energy savings from measures average 14.8 percent. They range from 8.8 percent in Lumber and Wood Products (SIC 24) to 23.1 percent in Electronic and Other Electric Equipment (SIC 36). Other SIC groups with high potential system efficiency are Petroleum (SIC 29), Chemicals (SIC 28), and Paper and Allied Products (SIC 26).
- The numbers in blue show the SIC/System Type combinations in which potential system savings are heavily concentrated. These 22 (out of 126) groups account for 69 percent of all potential savings identified through this study.

Table 2-13: Potential Energy Savings from System Efficiency Measures by SIC

		Estimated Savings (GWh/Year)								
SIC	Industry Category	Fan System	Pump System	Compressed Air Systems	Other Proc. Systems	Motor Upgrade	Motor Downsizing	Replace vs. Rewind	All Systems	As % of Total Energy
20	Food and Kindred Products	157	1,250	494	517	1,376	585	295	4,674	12.4%
21	Tobacco Products									
22	Textile Mill Products	170	593	408	166	743	305	121	2,506	15.0%
23	Apparel & Other Textile Products	1	0	68	15	47	22	8	162	13.9%
24	Lumber and Wood Products	153	243	324	341	432	336	184	2,013	8.8%
25	Furniture and Fixtures	87	5	78	33	173	68	26	471	12.7%
26	Paper and Allied Products	1,082	6,293	773	881	3,197	845	870	13,942	14.0%
27	Printing and Publishing	52	17	74	90	305	153	39	731	12.3%
28	Chemicals and Allied Products	942	7,556	6,813	994	4,219	1,409	1,255	23,188	16.1%
29	Petroleum and Coal Products	271	6,159	1,352	169	1,736	459	453	10,599	20.4%
30	Rubber and Misc. Plastics Products	113	1,851	813	411	1,498	435	303	5,424	14.8%
31	Leather and Leather Products	27	0	0	0	22	6	3	58	11.8%
32	Stone, Clay, and Glass Products	31	18	96	20	117	45	14	343	15.4%
33	Primary Metal Industries	738	1,537	2,150	1,085	3,199	983	749	10,441	11.9%
34	Fabricated Metal Products	34	181	303	80	298	195	46	1,137	15.6%
35	Industrial Machinery and Equipment	28	195	200	94	368	208	44	1,138	15.4%
36	Electronic and Other Electric Equipment	18	1,554	513	43	609	222	93	3,053	23.1%
37	Transportation Equipment	353	1,109	941	242	1,195	340	235	4,415	14.9%
38	Instruments and Related Products	71	119	123	78	263	169	39	862	13.3%
39	Misc. Manufacturing Industries									
	All Industry Groups	*4,330*	*28,681*	*15,524*	*5,259*	*19,799*	*6,786*	*4,778*	*85,157*	*14.8%*

Numbers printed in blue show SIC/system types with greatest potential for systems savings.

MOTOR DOWNSIZING

Table 2-14 shows our estimates of potential savings associated with better matching of motors to the load they drive. On the whole the savings are greatest for the smaller motors, especially in pumps and other applications. Air compressors have the lowest savings potential because we found that relatively few of the motors that drove air compressors were underloaded.

Table 2-14: Savings from Motor Downsizing

	Potential Motor System Energy Savings (% of Energy)				
Size Category (HP)	**Fan Systems**	**Pump Systems**	**Compressed Air Systems**	**Other Process**	**Total**
1–5	7.6%	6.3%	0.3%	7.5%	7.1%
6–20	0.5%	1.6%	0.6%	2.1%	1.6%
21–50	0.5%	0.2%	0.1%	1.1%	0.6%
51–100	0.7%	0.8%	0.2%	1.5%	1.0%
101–200	0.1%	0.3%	0.3%	1.1%	0.7%
201–500	0.0%	0.9%	1.2%	0.8%	0.8%
501–1000	0.0%	0.9%	1.2%	0.8%	0.7%
1000+	0.0%	0.9%	1.2%	0.8%	0.8%
All Motor Sizes	***0.6%***	***1.0%***	***0.9%***	***1.5%***	***1.2%***

MOTOR EFFICIENCY UPGRADES

EFFICIENT REPLACEMENT

Estimates of savings available from upgrading the efficiency of motors currently in place at the point of replacement are shown in Tables 2-15 and 2-16. These tables display motor system energy savings attributable to efficient replacement by horsepower category and SIC group respectively. As discussed on pages 63 and 64, neither the EPAct nor the CEE standard applies to motors over 200 horsepower. However, we estimated energy savings in horsepower ranges above 200 by applying the relevant efficiencies for 200 horsepower motors to observations of nominal efficiency for motors currently in place.

Tables 2-15 through 2-17 support the following findings in regard to potential energy savings from efficient replacement.

Overview

- For all manufacturing SICs, motor system efficiency savings associated with upgrading the efficiency of all motors currently in use to EPAct standards total 13.1 billion kWh per year. This is 18 percent of the total midrange potential savings estimate, and 2.3 percent of total manufacturing motor system energy consumption.
- Upgrading the efficiency of all motors in use to the higher CEE standards yields an additional 6.7 billion kWh per year. This would bring total savings from efficient replacement to 19.8 billion kWh, which is equivalent to 23.2 percent of the total midrange potential savings estimate and 3.4 percent of total manufacturing motor system energy use.

Distribution of Savings by Horsepower Category

- In terms of GWh per year, potential energy savings from efficient replacement is distributed fairly evenly among the horsepower categories. The lower horsepower categories show higher percentage savings than the larger motors. This is the result of the larger difference in (pre-1997) standard efficiencies and EPAct-compliant efficiencies in the smaller horsepower ranges described on pages 63 and 64.

Distribution of Savings by SIC Group

- For individual two-digit SIC groups, potential motor system energy savings from efficient replacements range from 1.9 percent of total motor system energy to 2.9 percent for EPAct level upgrades; 2.9 to 4.1 percent for CEE level upgrades.
- The difference in savings potential among the SICs is related to the representation of smaller motors in the population. Thus, for example, the Plastics industry shows a substantially higher level of potential savings than Chemicals or Paper.

Table 2-15: Savings from Motor Efficiency Upgrades by HP

	Savings from Upgrading to EPAct Standards		Savings from Upgrading to CEE Standards	
Size Category (HP)	**GWh/Year**	**% of Total Energy Use**	**GWh/Year**	**% of Total Energy Use**
1–5	1,221	4.4%	1,824	6.6%
6–20	1,925	3.2%	2,972	4.9%
21–50	1,971	2.7%	2,767	3.8%
51–100	1,487	2.0%	2,213	3.0%
101–200	1,438	1.7%	2,105	2.5%
201–500	1,625	1.8%	2,617	2.9%
501–1000	1,689	2.2%	2,618	3.4%
1000+	1,688	1.9%	2,683	3.0%
All Motor Sizes	***13,043***	***2.3%***	***19,799***	***3.4%***

Table 2-16: Savings from Motor Efficiency Upgrades by SIC

	Savings from Upgrading to EPAct Standards		Savings from Upgrading to CEE Standards	
Industry	**GWh/Year**	**% of Total Energy Use**	**GWh/Year**	**% of Total Energy Use**
28 Chemicals	2,720	1.9%	4,219	2.9%
26 Paper	2,078	2.1%	3,197	3.2%
33 Metals	2,104	2.4%	3,199	3.6%
29 Petroleum	1,137	2.2%	1,736	3.3%
20 Food	904	2.4%	1,376	3.6%
30 Plastics	1,053	2.9%	1,498	4.1%
Other	3,048	2.6%	4,573	3.9%
All Industry Groups	***13,043***	***2.3%***	***19,799***	***3.4%***

IMPROVED REWINDING PRACTICES

Table 2-17 shows estimates of energy savings associated with improved rewinding practices. We calculated both the annual and “full cycle” savings by applying the appropriate savings fractions shown in Table 2-11 to total annual motor system energy in each of the horsepower categories. Full cycle savings amount to 4.8 billion kWh per year. Annual savings are 0.4 billion kWh per year. The rewind cycles vary considerably by motor size. At average annual hours of operation, motors under 20 horsepower fail within 11 to 15 years; motors over 100 horsepower fail once in 5 to 8 years.

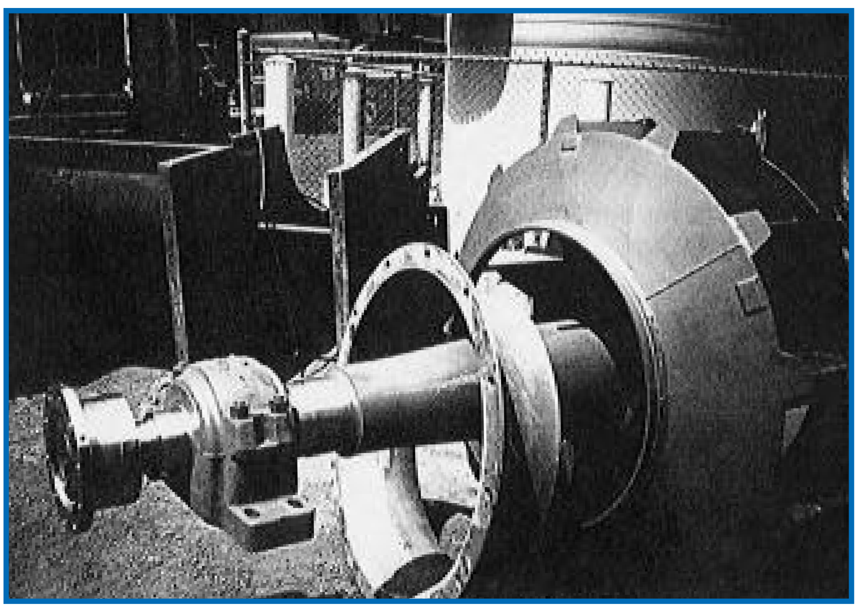
Table 2-17: Replace vs. Rewind Savings

Size Category (HP)	Motor System Energy (GWh/Year)	Annual Savings (GWh/Year)	Full Cycle Savings (GWh/Year)
1–5	27,776	29	56
6–20	60,122	70	367
21–50	73,111	65	592
51–100	72,924	44	656
101–200	83,099	39	756
201–500	90,819	51	826
501–1000	77,238	51	703
1000+	90,307	61	822
All Motor Sizes	***575,428***	***410***	***4,778***

PATTERNS OF POTENTIAL SAVINGS IN INDIVIDUAL INDUSTRIES

Just as patterns of motor system energy use vary significantly between different industries, so too do patterns of potential energy savings. Figure 2-2 shows the distribution of potential energy savings from major measure groups for facilities in the Paper and Allied Products (SIC 26) and Primary Metals (SIC 33) industries. Figure 2-2 that potential savings opportunities cluster in the application/horsepower groups with the greatest amounts of energy. Most of the savings in the paper industry are concentrated in improvements to pump systems. In Primary Metals, the largest savings can be found in large fan and air compressor systems. Savings in pump systems are also substantial in the lower horsepower ranges. The concentration of many of the savings opportunities in systems driven by large motors suggests that their implementation will require considerable planning and capital outlay. Appendix A contains similar charts for other industries with intensive motor energy use. Facilities managers and equipment vendors alike can use these figures as a guide for exploring motor system energy savings opportunities in their facilities.

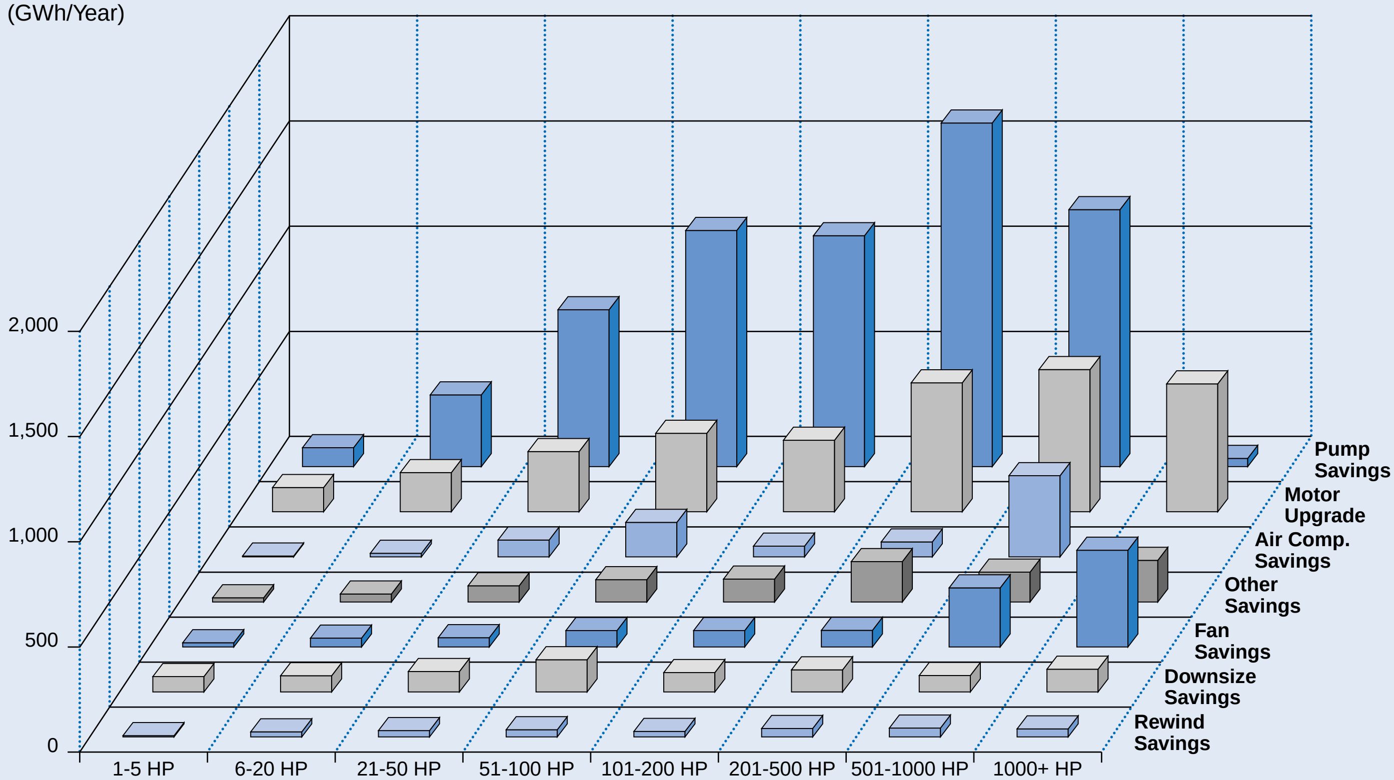
A steel producer optimized its fume collection system by tipping a fan impeller. Fan optimization projects result in large savings in the Primary Metals industry.



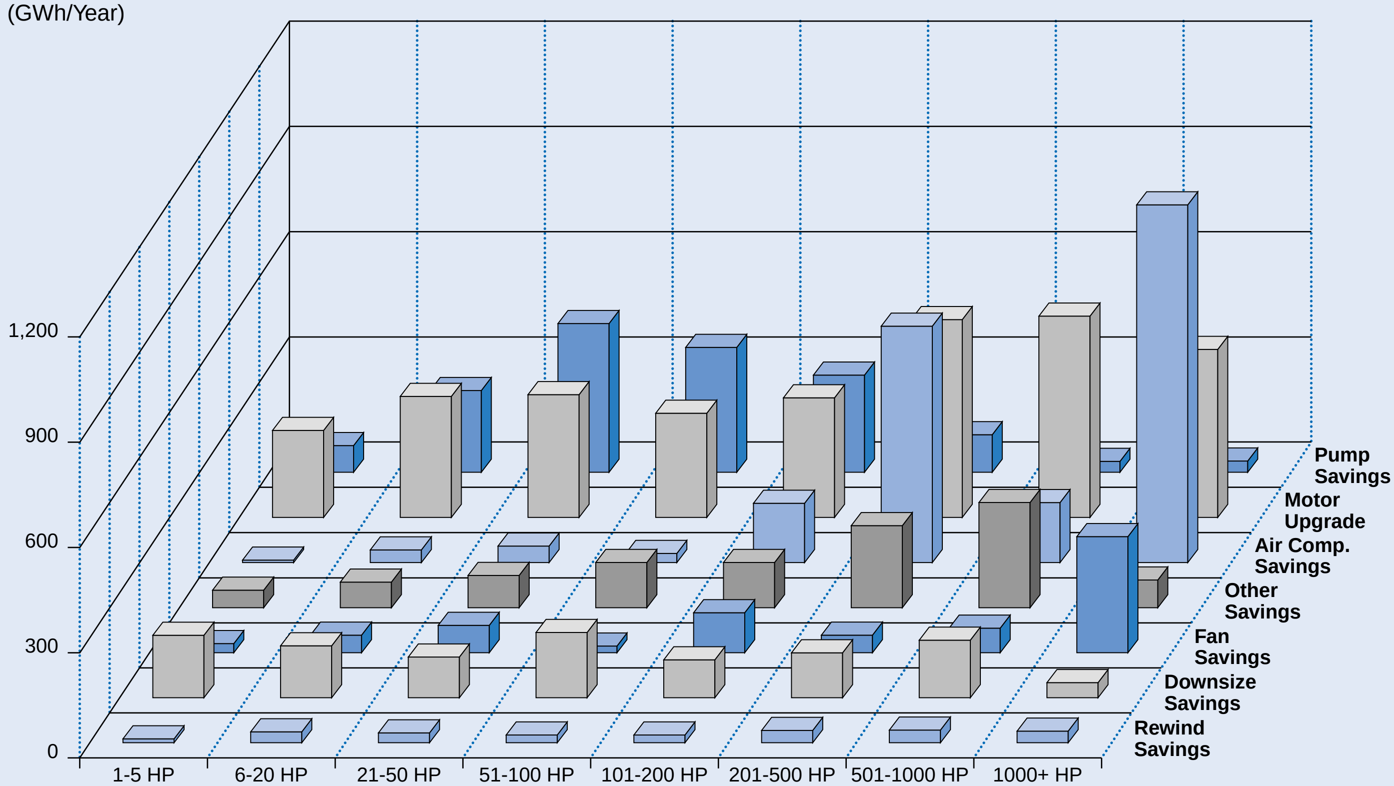
Flowcare Engineering, Inc.

Figure 2-2: Distribution of Potential Energy Savings by Application and Motor Size

Paper and Allied Products (SIC 26)
(GWh/Year)



Primary Metals (SIC 33)
(GWh/Year)



Section 3: Motor System Purchase and Management Practices

INTRODUCTION

This section presents key results of the motor systems Practices Inventory. Achievement of significant increases in motor system efficiency depend to a large extent on the adoption of good design, purchase, and management practices. Motor systems require continual monitoring and maintenance to run at their design efficiency. Each decision and action in the daily stream of motor system design, purchase, and maintenance carries with it consequences for energy efficiency and consumption. The Practices Inventory gathered information on the prevalence in the sample facilities of actions identified by industry experts as “good practice.”

Through the Practices Inventory, we sought information on a number of other issues central to the design and marketing of the Motor Challenge Program. These included:

- Which individuals within an industrial organization make various motor system purchase and management decisions?
- What criteria do these individuals apply to motor system purchase and management decisions?
- To what extent are facilities managers and staff aware of the elements of good motor system purchasing and management practice?
- What barriers inhibit facilities managers and engineering staff from implementing elements of good practice?

Due to time constraints on site and the extreme complexity of the Motor Systems Inventory, we chose to keep the Practices Inventory brief. We therefore did not have time to explore the full range of “market barriers” which affect the implementation of motor system efficiency measures or the structural and operating issues which affect decisions regarding allocation of capital expenditures to various strategic objectives. On the other hand, the results of the Practices Inventory do support a number of clear conclusions about the challenges of reaching decision makers in industrial organizations and of changing their motor systems purchasing and management practices. These can be summarized as follows:

- Most purchase and maintenance decisions that affect motor systems efficiency are made at the plant level, even in large companies with national multi-facility operations.
- Few facilities managers have implemented more than one or two elements of good motor systems purchasing and maintenance practices. Many had implemented none.
- Lack of information concerning the nature of motor system efficiency measures—their benefits, costs, and implementation procedures—constitutes a principal barrier to their adoption.
- While we did not explicitly question respondents concerning allocation of resources to motor system efficiency, the field engineers noted repeatedly the limited resources available for motor system monitoring and maintenance. The priority for facilities management and maintenance staff was to ensure continuity and consistency of mechanical operations. It was very difficult for facilities management staff to break away from their jobs long enough to answer a few questions or to provide escorts for the field engineers. There was clearly little slack in their schedule for the additional tasks required for active motor systems management—at least without considerable guidance concerning the most worthwhile allocation of resources. These informal observations have been confirmed by many engineers and utility program staff who provide services to industrial customers.

The results of the survey highlighted the need for Motor Challenge and similar programs to:

- Increase the visibility and credibility of information on the potential benefits of motor system efficiency measures.
- Facilitate the implementation of such measures by end-users and vendors in the market.

The paragraphs below present detailed findings from the Practices Inventory. All percentages reflect the effects of weighting the responses from individual sample facilities for their representation in the population.

MOTOR PURCHASE DECISION-MAKING

LOCUS OF DECISION-MAKING

The results of the inventory clearly show that decisions regarding motor purchases are made at the plant versus the corporate level. First, as Table 3-1 shows, 77 percent of all manufacturing plants are sole locations for their respective companies. Ninety percent of sole locations are in the small and small/medium size categories. A higher percentage of large plants are branches of big companies.

Table 3-1: Branch/Sole Locations by Facility Size

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Sole Location	46%	55%	71%	71%	80%	**77%**
Branch or Subsidiary	54%	45%	29%	29%	10%	**16%**
No Answer	0%	0%	0%	0%	9%	**7%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

Even in plants that are subsidiaries of larger companies, motor purchase decisions are made at the factory level. Table 3-2 shows results only for factories which were identified as branch facilities or subsidiaries of larger organizations. Overall, 91 percent of facilities personnel in multi-plant companies reported that motor purchase decisions are made at the plant level. The percentage was even higher for larger facilities.

Table 3-2: Location of Motor Purchasing Decisions for Facilities with Multiple Locations

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Decision made at plant	96%	92%	100%	88%	91%	**91%**
Decision made at HQ	0%	6%	0%	9%	5%	**5%**
Decision depends on purchase	4%	2%	0%	2%	5%	**4%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

The individual responsible for motor purchasing decisions varies by the size of company, as can be seen in Table 3-3. In larger companies, the maintenance manager is primarily responsible for motor purchase decisions. Whereas in smaller companies, the majority of motor purchasing decisions are made by the president or CEO.

Table 3-3: Position of Inventory Respondent (Person Who Makes Motor Purchase Decisions)

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Plant Manager	0%	17%	0%	12%	14%	**13%**
Maintenance Manager	41%	43%	72%	5%	3%	**9%**
Purchasing Manager	0%	0%	0%	20%	0%	**2%**
Plant Engineer	16%	8%	12%	2%	4%	**5%**
Chief Electrician	23%	4%	4%	1%	0%	**1%**
President or General Manager	0%	0%	4%	35%	47%	**40%**
Other	20%	24%	8%	25%	31%	**29%**
(blank)	0%	4%	0%	0%	0%	**1%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

MOTOR PURCHASING PRACTICES

AWARENESS OF ENERGY-EFFICIENT MOTORS

Overall, awareness of energy-efficient electric motors among the facilities personnel surveyed was relatively low. Excepting large companies, a very small percentage of motor purchasers reported being aware of premium efficiency motors. As Table 3-4 shows, only 19 percent of all respondents were aware of premium-level efficient motors.

Table 3-4: Percent of Motor Purchasers Reporting Awareness of Premium Efficiency Motors by Facility Size

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Aware	97%	42%	35%	38%	12%	**19%**
Not Aware	3%	58%	65%	62%	72%	**69%**
No Answer	0%	0%	0%	0%	16%	**12%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

With the exception of companies in the Chemical and Allied Products industry, awareness of premium efficiency motors was higher in industries with higher amounts of electric motor use. These include Pulp and Paper, Petroleum, Rubber, and the Primary Metals industries.

Awareness of energy-efficient electric motors is generally low, except with the large users of electric motor systems, such as petroleum refineries.

Table 3-5: Percent of Motor Purchasers Reporting Awareness of Premium Efficiency Motors by SIC

	SIC Categories							
	Food	Paper	Chemical	Petroleum	Rubber	Metals	Other	Total
Aware	35%	66%	31%	69%	73%	78%	8%	**19%**
Not Aware	21%	30%	69%	31%	27%	22%	78%	**69%**
No Answer	44%	3%	0%	0%	0%	0%	14%	**12%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

Overall, only 4 percent of respondents reported they were aware of the efficiency ratings associated with the "High or Premium" designation. An additional 38 percent reported they were somewhat aware of the efficiency implications of the designation. Representatives of larger companies tended to be more versed in this area than those of smaller companies.

Table 3-6: Percent of Motor Purchasers Reporting Awareness of Efficiency Ratings Associated with "High" or "Premium" Designation

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Yes	45%	10%	12%	3%	2%	**4%**
Somewhat	53%	55%	71%	62%	30%	**38%**
No	2%	35%	16%	34%	51%	**46%**
No Answer	0%	0%	0%	0%	16%	**12%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

Some care needs to be taken in interpreting the results of the Practices Inventory with regard to awareness of energy-efficient motors. During the time the survey was underway, motor dealers did not always use a consistent system of nomenclature for motors which met the efficiency standards promulgated by NEMA. Some companies referred to such motors as "high efficiency", others as "premium efficiency", and still others as "energy efficient." (The NEMA nomenclature for motors that met its standards was "energy efficient.") Moreover, some manufacturers labeled motors which did not meet NEMA standards as energy efficient. We tried to clarify the motors we were referring to through the wording of items in the questionnaire, but any confusion that respondents faced in answering these questions may have reflected inconsistencies in nomenclature in the market.

PURCHASES OF ENERGY-EFFICIENT MOTORS

Twenty-two percent of customers reported that they had purchased efficient motors over the 2 years prior to the Inventory. These purchasers were concentrated in larger company size categories and were in more motor-intensive industries. Table 3-7 shows that larger companies generally bought a higher percentage of efficient motors during the past 2 years. The pattern is not consistent in small to medium companies.

Table 3-7: Percent of Customers Who Bought Efficient Motors Over the Past 2 Years—
Average Percentage of New Motors that are Efficient by Facility Size

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
All motors energy efficient	9%	6%	3%	13%	4%	**5%**
Some motors energy efficient	77%	31%	15%	5%	17%	**17%**
No motors energy efficient	14%	50%	82%	79%	68%	**68%**
No Answer	0%	13%	0%	3%	12%	**10%**
Average % Energy Efficient	***29%***	***18%***	***6%***	***15%***	***11%***	***12%***

Purchase of efficient motors also varies considerably by SIC, even among large motor system energy users. Some of this variation may be due to the use of very large (over 200 HP) motors in certain industries such as chemicals and metals. These large motors are not covered by EPAct standards. However, a high proportion of respondents in the Petroleum industry (61 percent) reported that all motors purchased over the past 2 years had been energy efficient. The Petroleum industry is characterized by a high saturation of large motors.

Table 3-8: Percent of Customers Who Bought Efficient Motors Over the Past 2 Years—Average Percentage of New Motors that are Efficient by SIC

	SIC Categories							
	Food	Paper	Chemical	Petroleum	Rubber	Metals	Other	Total
All motors energy efficient	47%	20%	13%	61%	1%	1%	2%	**5%**
Some motors energy efficient	32%	24%	22%	5%	29%	34%	14%	**17%**
No motors energy efficient	14%	49%	53%	30%	70%	64%	72%	**68%**
No Answer	8%	7%	12%	3%	0%	0%	12%	**10%**
Average % Efficient	***58%***	***28%***	***23%***	***65%***	***4%***	***4%***	***9%***	***12%***

The overall findings on market penetration of energy-efficient motors are consistent with U.S. Census shipment figures. Over the past 3 years, the market penetration of efficient motors in the type and horsepower categories covered by the federal standards has averaged around 18 percent. In 1996, however, this percentage fell to 15 percent. The average percentage of energy-efficient motors purchased by respondents over the 2 years prior to the Inventory was 12 percent.

RESTRICTION IN REPLACING MOTORS IN OEM EQUIPMENT

Some motor system market observers have hypothesized that customers were inhibited from buying energy-efficient motors by restrictions on motor replacements made by machine manufacturers (OEMs). For example, for some kinds of specialized machines, only motors with particular frame sizes, physical configuration, or operating characteristics would work. Alternatively, warranties would be voided if replacement motors were supplied by unauthorized manufacturers.

We questioned the Practices Inventory respondents on these points. Table 3-9 summarizes their answers. We found that OEM restrictions on purchase of replacement motors affected roughly 60 percent of the companies represented. However, only 18 percent of the respondents mentioned that replacement motors were not available in premium efficiency models. We conclude, therefore, that OEM practices constituted a barrier to the purchase of energy-efficient motors prior to the promulgation of federal efficiency standards. However, this barrier appeared to affect a minority of manufacturers. Federal standards cover integral horsepower general purpose motors, including those packaged into other machines.

Table 3-9: OEM Restrictions on Equipment with Installed Motors

Restriction*	Percent Reporting
Replacement motors available only through OEM	22%
Replacement motors available only through one manufacturer	14%
Replacement with motors from unauthorized vendors voids warranty	7%
Replacement motors not available in premium efficiency models	18%
Other problems	10%
Not applicable to motors in facility	6%
No problems reported	33%

*Customers could name more than one restriction.

USE OF PURCHASE GUIDES

Some observers of industrial equipment markets hypothesize that customers are inhibited from purchasing efficient motors because they rely primarily on vendors to make selections of the appropriate motors for various applications. They further hypothesized that, until recently, vendors faced disincentives to stocking efficient motors due to their higher costs. To assess this hypothesis, we asked end-users about the sources of information they used in selecting new and replacement motors. We were particularly interested in finding out whether customers used compilations of product information to support independent judgments on motor selection. We found that only one one-quarter of customers are aware of any publications or tools whatsoever for guiding purchase of new and replacement motors. The percentage is significantly higher only among the very largest customers. See Table 3-10.

Table 3-10: Percentage of Customers Aware of Tools for Selecting New or Replacement Motors

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Yes	71%	33%	23%	37%	22%	**25%**
No	29%	66%	77%	63%	59%	**61%**
No Answer	0%	1%	0%	0%	19%	**14%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

The most frequently used references for motor selection were manufacturers' catalogs. Only 5 percent of customers reported using these sources regularly. The corresponding figure for large customers was 17 percent. See Table 3-11. While nearly one-half of the large customers interviewed reported being aware of the MotorMaster+ software, which provides extensive support for motor selection and inventory management, only one reported having actually used it.

Table 3-11: Awareness and Usage of Manufacturers' Catalogs for Motor Selection

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Not aware	1%	3%	0%	4%	2%	**2%**
Have heard of	0%	7%	1%	0%	16%	**13%**
Have used it	53%	10%	3%	23%	3%	**6%**
Use it regularly	17%	6%	17%	13%	2%	**5%**
No answer	29%	74%	79%	59%	77%	**75%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

MOTOR PURCHASE POLICIES

Adopting standard policies and specifications for purchasing efficient motors will help in replacement situations where quick action is needed to avoid downtime.

The Motor Challenge Program and similar utility-sponsored efforts encourage customers to adopt standard policies and specifications for purchasing efficient motors. This can be particularly important for ensuring the purchase of efficient models in replacement situations where quick action is needed to keep production up and running. Overall, only 3 percent of customers reported that their companies had adopted a policy regarding the efficiency of new motors purchased. As Table 3-12 shows, virtually all of these are among the largest customers.

Table 3-12: Prevalence of Motor Purchase Policies

	Size Categories					
	Large	**Med/Large**	**Medium**	**Sm/Med**	**Small**	**Total**
Have efficiency policy	20%	9%	5%	13%	1%	**3%**
No policy	80%	80%	75%	85%	67%	**70%**
No answer	0%	11%	19%	2%	32%	**26%**
Total	***100%***	***100%***	***100%***	***100%***	***100%***	***100%***

Only 11 percent of the companies that participated in the Inventory reported having had written specifications for motor purchases. Only two-thirds of these companies reported including efficiency in their specifications. Items included in those specifications are shown in Table 3-13.

Table 3-13: Company Purchasing Specifications

Specification	**Percent Reporting**
Temperature rise/Insulation class	11%
Maximum starting current	8%
Minimum stall time	5%
Power factor range	5%
Efficiency and test standard	7%
Load inertia	3%
Expected number of starts	7%
Suitability to facility operating environment	9%
Ease of reparability	4%

MOTOR SIZING PRACTICES

Instantaneous load measurements conducted as part of the Motor Systems Inventory found that over 40 percent of motors in use were operating at less than 40 percent part load. These findings suggested that the practice of oversizing motors was widespread. Customers' responses to criteria used to select the size of replacement motors was consistent with these findings. Inventory respondents reported using the size of the motor being replaced most often as the criterion for selecting the size of new motors. This practice would tend to perpetuate any oversizing in the selection of the original motor.

Table 3-14 shows the pattern of response to questions concerning the methods used to determine the size of replacement motors. Respondents could report using more than one method. Using the size of the motor replaced was by far the most frequently reported sizing method. Eighty-six percent of customers reported using it all or most of the time. By contrast, 44 percent of customers reported using equipment manufacturers' specifications as a guide to sizing all or most of the time. Moreover, 29 percent of customers used the size of replaced motor as their only sizing criterion. These customers are mostly in the small- and medium-size ranges.

Table 3-14: Frequency of Criteria for Selecting Motor Size

	Always	Most of the time	Some of the time	Never	No Answer	Total
Select the same size as the motor being replaced.	55%	31%	4%	0%	11%	100%
Use motor in inventory closest in size to motor being replaced.	5%	10%	20%	41%	24%	100%
Select motor size based on load measurements or estimates.	7%	3%	12%	55%	23%	100%
Select motor size based on production equip. specifications.	24%	20%	8%	25%	23%	100%

REWINDING PRACTICES

There are two major energy saving opportunities associated with rewind practices. The first is to encourage customers to replace failed motors with more efficient models rather than rewind them. The second is to ensure that customers specify and rewind shops use best practices so that degradation of efficiency is minimized. The Practices Inventory contained an extensive series of questions on the proportion of motors that customers rewound, the criteria applied to the rewind/replace decision, and the use of written rewind specifications. The responses to these items are detailed below.

PERCENTAGE OF MOTORS REWOUND

Respondents were asked to report on the percentage of motors they rewind in each horsepower category. The results from these questions are shown in Table 3-15. Not surprisingly, the percentage of motors rewound upon failure increases with size. This is largely because the difference in cost between purchasing a replacement motor and rewinding the failed unit increases with size.

Table 3-15 shows a number of unexpected results. First, a large percentage of customers report rewinding failed motors in the 1–5 horsepower category. Several studies of the rewind industry have found that it is less expensive, even on the basis of first costs alone, to replace motors in this size category than it is to rewind them.[1] One possible explanation of this finding is that the smaller motors rewound are special purpose items which are difficult and costly to replace. Second, small facilities report that they rewind smaller motors more frequently than large ones. This finding likely reflects the fact that there are very few motors above 50 horsepower in small facilities.

Table 3-15: Percentage of Motors Rewound By Horsepower Category and Facility Size

	Large	Med/Large	Medium	Sm/Med	Small	Total
1–5 HP	19%	20%	16%	19%	23%	**20%**
6–20 HP	62%	62%	55%	50%	68%	**61%**
21–50 HP	84%	80%	83%	79%	79%	**81%**
51–100 HP	90%	90%	86%	87%	94%	**90%**
101–200 HP	***94%***	***89%***	***93%***	***85%***	***97%***	***91%***

Respondents to the Practices Inventory reported that they rewound a given motor three times, on average. Larger motors tend to be rewound more often than smaller ones.

FACTORS CONSIDERED IN REWIND DECISION

Respondents to the Practices Survey were asked to indicate whether they took various considerations into account in their replace versus rewind decisions. Table 3-16 summarizes the answers to this series of items.

[1] One recent study of the practices of rewind shops placed the “break-even point” at 10–12 horsepower. (Douglass et al., 1995) However, it should be noted that the price relationship between replacement purchases and rewinds fluctuates with price changes in the motors market and the costs of materials and labor in the motor service business.

Table 3-16: Factors Considered in Rewind Decision*

	Large	Med/Large	Medium	Sm/Med	Small	Total
Capital cost of rewound motor vs. cost of new motor	91%	80%	55%	43%	63%	**62%**
Installation cost of rewound motor vs. installation cost of new motor	2%	17%	0%	17%	2%	**5%**
Cost of electricity used by rewound motor vs. electric cost of new motor	6%	11%	8%	31%	10%	**12%**
Reliability of rewound motor vs. reliability of new motor	4%	20%	11%	6%	19%	**17%**

*Respondents could name more than one factor.

The results shown in Table 3-16 clearly show that the replace/rewind decision is driven by considerations of first costs. Sixty-two percent of respondents reported that they considered the capital cost of the rewind versus the cost of the new motor in making their decision. By contrast, only 12 percent considered the relative energy costs of the two options and 17 percent took the reliability of rewound versus new motors into account. Larger customers appeared to put a larger weight on capital costs than smaller customers. This may reflect the fact that larger customers tend to have larger motors, for which the differential costs of rewinding and replacing are larger.

PUMP, FAN, AND COMPRESSOR SYSTEM EFFICIENCY PRACTICES

Customers were asked whether they had undertaken any of a long list of system efficiency measures over the past 2 years. They were not asked how often they carried out the measures or whether they constituted a regular practice. Compressed air systems appeared to have received the most attention, with 20 percent of all respondents reporting that they fixed leaks and 6 percent reporting that they replaced single stage rotary screw compressors with more efficient models. Except among the very largest customers, pump and fan systems were virtually ignored.

As would be expected, large facilities made the most system efficiency improvements. Measures which they implemented with some frequency included:

- Retrofit of fan systems with ASDs: 20 percent;
- Retrofit of duct systems with inlet guide vanes: 9 percent;
- Substitution of ASDs for throttling valves in pump systems: 22 percent;
- Installation of parallel pumps to respond to load variations: 14 percent;
- Use of parallel compressors to respond to load variations: 23 percent;
- Reconfigured piping and filters to reduce pressure drops in compressed air systems: 14 percent;
- Added multi-unit controls to reduce part load consumption in compressed air systems: 23 percent;
- Reduce the size of compressors to better match load: 10 percent; and,
- Fixed leaks in compressed air systems: 42 percent.

Table 3-17: Reported System Measures Undertaken During the 2 Years Prior to the Inventory

	Size Categories					
	Large	Med/Large	Medium	Sm/Med	Small	Total
Fan Systems						
Retrofitted with ASDs	20%	7%	1%	0%	1%	**1%**
Retrofitted with inlet guide vanes	9%	1%	0%	0%	3%	**2%**
Checked components with large pressure drops	3%	1%	10%	0%	3%	**3%**
No fan systems in facility	0%	29%	24%	18%	43%	**38%**
No improvements	67%	49%	45%	80%	33%	**40%**
Pump Systems						
Substituted speed controls for throttling	22%	8%	11%	1%	0%	**1%**
Used parallel pumps to respond to variations in load	14%	4%	2%	0%	3%	**2%**
Reduced pump size to fit load	0%	5%	7%	11%	3%	**4%**
Increased pipe diameter to reduce friction	5%	6%	6%	11%	1%	**3%**
No pump systems in facility	13%	28%	24%	17%	40%	**35%**
No improvements	45%	57%	42%	52%	34%	**38%**
Compressed Air Systems						
Replaced 1-stage rotary screw units with more efficient models	7%	16%	29%	2%	4%	**6%**
Used parallel compressors to respond to variations in load	23%	12%	10%	13%	7%	**8%**
Reconfigured piping and filters to reduce pressure drops	14%	24%	5%	13%	1%	**5%**
Added multi-unit controls to reduce part load consumption	23%	10%	6%	0%	4%	**4%**
Reduce size of compressors to better match load	10%	6%	1%	2%	1%	**1%**
Fixed leaks	42%	40%	34%	36%	15%	**20%**
No compressed air systems in facility	0%	3%	0%	1%	10%	**8%**
No improvements	39%	44%	37%	62%	52%	**52%**
No Reported Improvements	30%	27%	14%	45%	21%	**24%**

Table 3-17 also shows that a large proportion of customers had not taken any of the common systems related measures over the 2 years prior to the inventory. Specifically:

- 40 percent of customers had undertaken none of the listed fan system measures;
- 38 percent had undertaken none of the listed pump system measures;
- 52 percent had undertaken none of the listed compressed air system measures; and,
- 24 percent had undertaken none of the systems measures at all.

These results do not include customers who reported that they had none of the various kinds of motor systems in their facilities.

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